The internationalisation of green technologies and the realisation of green growth

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Declaration

I certify that the thesis I have presented for examination for the PhD degree of the London School of Economics and Political Science is solely my own work other than where I have clearly indicated that it is the work of others (in which case the extent of any work carried out jointly by me and any other person is clearly identified in it).

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Abstract

This thesis investigates how the 'spatialisation' of green technologies influences opportunities to realise green growth from different industrial activities – an aspect of green growth which is currently underrepresented in the literature. The research compiles various datasets representing world-wide indicators of innovation and manufacturing, as well as interviews with researchers and industrial actors in different economies, to investigate the spatialisation of solar photovoltaic (PV) industries. The overarching purpose is to examine whether domestic economies need both innovation and manufacturing in order to supply green technologies.

The thesis comprises of four standalone chapters (Chapter 2 to 5) that explore this question by applying evolutionary economic geography (EEG) theory on the concept of green growth. The first chapter (Chapter 2) develops a conceptual framework on how the spatialisation of technologies affects the composition of industrial activities in various economies. It argues the localisation of green innovation enables economies to be resilient to the loss in manufacturing. The second chapter (Chapter 3) demonstrates that both 'first-mover' and 'late-comer' economies contribute towards solar PV innovation, despite the majority of global manufacturing shifting to China. The third chapter (Chapter 4) finds patterns of research collaboration between different countries based on their respective innovation/manufacturing intensities. The last chapter (Chapter 5) explores how the presence (or absence) of domestic manufacturing influences actors' commercialisation of different solar PV technologies.

The findings seek to advance the competitiveness debate by recognising the tension between the internationalisation of green technologies and the realisation of green growth in domestic economies. First, it argues that economies realise long-term green growth by retaining high-value activities that other economies cannot reproduce. Second, it recognises that an economy does not need both innovation and manufacturing to commercialise green technologies, but that the propensity to rely on local resources is influenced by the domestic industrial composition and the maturity of a technology. These findings emphasise that industrial policies should consider spatial characteristics in assessing whether domestic green technology supply and/or markets will lead to green growth in the domestic economy.

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Apparently the PhD constitutes this book that you are about to read – assuming you will be reading it, and not just the acknowledgements. But if you are going to read the acknowledgements, let me take the opportunity to assure you that getting a PhD goes beyond this codified piece of work. It is the entire experience of trying to become an academic, and that experience not only involves the training and the courses, but also the entire psychosis involved with the metaphorical and literal "walking in circles" to find some sense of truth. There is no way that one can go through this entire experience without recognising the brilliant people who have helped me to get to the light at the end of the tunnel. Truly, I am grateful to every single person who has helped me in this journey of becoming an academic.

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Chapter 1: Thesis introduction

The internationalisation of green technologies and the implications of realising green growth

> *"Meanwhile, China is not waiting to revamp its economy. Germany is not waiting. India's not waiting. These nations are not standing still. These nations are not playing for second place…They're making serious investments in clean energy because they want those jobs. Well I do not accept second place for the United States of America… Because the nation that leads the clean energy economy, is the nation that leads the global economy. And America must be that nation."*
>
> – President Barack Obama, 2010 State of the Union Address

1.1 Introduction

Domestic support for green technologies undergoes techno-national debates as both developed and emerging economies invest in green industries (Barua, Tawney, & Weischer, 2012; Dutz & Sharma, 2012). The race for green technologies implies that domestic economies' opportunities to realise green growth is threatened by global competition. The current literature addresses this issue by undertaking empirical analysis of which countries have been successful in green innovation (Fankhauser et al., 2013; Johnstone, Haščič, & Popp, 2009). This literature is certainly relevant to understanding the importance of innovation. It is less adept at explaining why manufacturing of green technologies can still shift to foreign economies – thereby appearing to invalidate the long-term growth rationale for green industrial policy. Another set of literature compares how various countries develop national innovation systems for green technologies – including those who entered the industry through manufacturing (Bergek et al., 2008; Kamp, Smits, & Andriesse, 2004; Lo, Wang, & Huang, 2013). Though this literature does highlight the different approaches countries take in establishing green industries, it does not consider how the spatial dynamics of technologies can affect the amount of economic growth countries can realise from these industries. Understanding the spatial shifts of industrial activities – and the implications on value-added to the economy – are important in addressing when and how various economies can realise green growth.

Therefore this thesis investigates how the spatialisation of green technologies influences opportunities to realise green growth from different industrial activities. Its first aim is to demonstrate how an evolutionary economic geography (EEG) perspective is useful to green growth literature. First, EEG recognises how the spatial characteristics of technologies affect where industrial activities locate as technologies mature. Second, these spatial characteristics have implications about the levels of economic value that economies can achieve from innovation and manufacturing activities in the short and long-term. Third, these spatial dynamics can provide a balanced assessment of whether green growth in the domestic economy will be realised from domestic supply and/or domestic markets for green technologies.

The second aim of the thesis is to examine whether domestic economies need both innovation and manufacturing in order to commercialise green technologies. Both EEG and systems failure literature argue that both research and industrial actors need to be located close to each other in order to enable continuous learning feedback loops (Woolthuis, Lankhuizen, & Gilsing, 2005; Ponds, van Oort, & Frenken, 2007). However this thesis considers countries that have high technological capabilities but low industrial capacity. Technological capabilities refer to the ability of economies to manage technological change – including the ability to commercialise technologies (Bell & Pavitt, 1997; Watson et al., 2014). Industrial capacity simply refers to an economy's ability to manufacture existing technologies (Bell & Albu, 1999; Lall, 1994). Does the lack of a domestic industry jeopardise these countries ability to commercialise technologies?

This thesis uses the solar photovoltaic (PV) industry as a case study to explore these aims. The research compiled various datasets representing global-wide indicators of innovation and manufacturing between 1990 and 2012. The data also include interviews with solar PV researchers and industrial actors who are based in different economies. In doing so, it can compare how countries' composition of research and manufacturing in solar PV technologies changed in two different time periods. The first time period (1990-2004) characterises the dominance of 'first-mover' countries (such as Japan, USA and Germany) in contributing to both global research and manufacturing (Liebreich, 2011). These countries are characterised as first-movers because they engaged in the early commercialisation for these technologies. The second time period (2005-2012) is an inflection point when China – as a late entrant (a.k.a. late-comer) increased its industrial capacity to surpass the size of first-mover countries (Zindler, 2012).

Therefore exploring the research and manufacturing dynamics of the solar PV industry is useful to this thesis's research for two reasons. It can juxtapose countries' contributions to global research and manufacturing in these time periods to see whether shifts in manufacturing result in similar spatial shifts in research. The purpose is to ascertain how the spatial relationship between innovation and manufacturing changes over time at the global level. Second it can identify cross-sections of countries that demonstrate various levels of technological capabilities and industrial capacity. Therefore through comparing research collaborations of these countries, along with the findings from the interviews, the thesis can discuss how the presence (or absence) of domestic industry affects these research actors' commercialisations efforts.

Aside from the introduction and conclusion chapters, the thesis is divided into four standalone chapters. Chapter 2 develops a conceptual framework on how the spatialisation of technologies affects the composition of industrial activities in various economies. It argues the 'localisation' of green innovation enables economies to be resilient to the loss in manufacturing. Chapter 3 demonstrates that both first-mover and 'late-comer' economies contribute towards solar PV innovation. These developments occur despite the majority of global manufacturing for crystalline PV products shifting to China. Chapter 4 finds patterns of who foreign countries undertake research collaborations with, based on their own level of technological capabilities/industrial capacities. Chapter 5 explores how the presence (or absence) of domestic manufacturing influences actors' commercialisation efforts in different solar PV technologies.

The findings seek to advance the competitiveness debate by recognising the tension between the spatialisation of technologies and 'localisation' of green growth. First it argues that economies realise long-term green growth by retaining high-value activities that other economies cannot reproduce – i.e. demonstrating their resilience to global competition. Second it recognises that an economy does not necessarily need both innovation and manufacturing to commercialise green technologies. However the propensity to rely on local resources is influenced by the domestic industrial composition and the maturity of a technology – a nuance that is currently not explicitly found in the EEG literature. These findings emphasise that industrial policies targeted towards specific green technologies should pay attention to their spatial characteristics. Broader green growth literature can also use this spatial framework to consider how countries competitiveness in green technologies is based on this concept of resilience.

This rest of this introductory chapter is organised as follows. Section 2 covers the key literature associated with each aim of this thesis, highlighting the gaps in the literature that this thesis seeks to address. This section ends by writing key conceptual questions that can help in addressing these gaps. Section 3 describes the data that were gathered on the solar PV industry to explore these questions. Section 4 then provides an introduction to each chapter, focusing on how its findings can address the gaps in the literature. Section 5 ends with concluding remarks.

1.2 The need to re-examine the claims of green growth

1.2.1 Key premises of green growth

Most academic discourse on green growth is largely discussed within the environmental policy literature. The concept of green growth has arisen after the start of the global economic recession in 2008 (Barbier, 2010; Bowen et al., 2009). Facing the global crises of economic recessions and climate change, international organizations and national governments are structuring policies to encourage investments in industrial activities that reduce adverse impacts to the environment (Ekins, 2014; Robins, Clover, & Singh, 2009). Such economic activities include research, development and deployment (RD&D) of green technologies – that is, those technologies that reduce the environmental impacts of the economy. Establishing these industries can provide economic growth through the creation of new industries, markets, and associated jobs (Hepburn & Bowen, 2012).

The concept of green growth stems from a rich background literature in environmental policy. The attraction of the term is that it is able to reconcile the priorities of sustaining natural capital whilst simultaneously creating endogenous economic growth opportunities (UNEP, 2011). This concept is perhaps best encapsulated in the Organisation of Economic Cooperation and Development's (OECD 2011, p.8) definition of green growth, which states:

> *"Green growth means fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies. To do this it must catalyse investment and innovation which will underpin sustained growth and give rise to new economic opportunities."*

Thus the three key aspects of green growth are (Hallegatte et al., 2011; Jacobs, 2012):

1. The need to sustainably preserve natural capital in the process of economic development.
2. That innovation (both technological and organizational) can be used to significantly decrease the impact on the environment.
3. Such innovation can provide long-run economic growth opportunities through improving production efficiencies, whilst creating new industries and markets in domestic economies.

Nevertheless even within environmental policy circles, green growth faces critiques. The first critique focuses on whether green technological innovation is a viable and sufficient solution in ensuring the sustainable management of environmental resources (Neumayer, 2003). These critiques stem from 'limits to growth' and 'strong sustainability' theories (Fitzpatrick, 2011). Their main underlying idea is that the global economy has exceeded the earth's ecological thresholds (Huesemann, 2003). Environmental policies are necessary to limit resource consumption and pollution – even if it imposes severe costs on economic growth (Meadows, Meadows, & Randers, 2004).

Though not necessarily a critique, literature on green growth focuses on the challenges on developing and deploying green technologies in the economy. These include the need to overcome market failures that do not account for the costs of pollution (particularly greenhouse gases); underinvestment in RD&D in green innovation; techno-institutional lock-ins in fossil fuel-dependent economies; and various government failures that inhibit the organizational changes needed to invest and deploy green technologies (Barbier, 2010; Hallegatte et al., 2011; Stern & Rydge, 2013). These market and government failures indicate the obstacles within the domestic economy that prevent the realisation of green growth. This thesis is interested in critically examining the third premise of green growth that focuses on endogenous economic growth. The justification of policy investments in developing green industries is that it can realise economic growth by selling technologies to domestic and foreign markets (Barua, Tawney, & Weischer, 2012). These include economies that indigenously innovate technologies, as well as those who enter the industry through manufacturing them. Consequently more economies are participating in the supply of green technologies (Zindler, 2012). Thus it becomes more challenging for individual economies to realise green growth from selling green technologies. It should be noted that this global competition occurs when there are low trade barriers that enable a plurality of firms to access domestic and foreign markets (Karp & Stevenson, 2012).

This first aim of the thesis is to integrate a more spatial perspective of technologies to understand which economies can benefit from green growth. This perspective is relevant as more countries compete in supplying these technologies to domestic and global markets. This perspective is also conceptually unique to other literature on green growth because it focuses on how spatial characteristics of technologies affects where industrial activities locate *over time* – and its implications on levels of green growth in different countries. Therefore it can address both short term and long-term green growth opportunities for different economies – not just from supply-side activities, but also from markets.

Whilst other studies have used specific measures of innovation and trade data to undertake this comparison, this thesis will use datasets of both innovation and manufacturing of solar PV data to undertake empirical comparisons. The purpose is to understand how the industrial composition of innovation and manufacturing within an economy changes over time – and how this compares to other countries. By being able to undertake this analysis, this thesis questions how the presence (or absence) of domestic industries affects research actors propensity to leverage domestic or international partners. This question underlies the second aim of the thesis. It therefore contributes to the literature in EEG by discussing how the size of domestic industries can influence patterns in *international* research collaborations. The following sub-sections will review the current literature that addresses these aims, and its limitations in explaining relevant spatial dynamics.

1.2.2 First aim: Integrate insight from EEG to understand which economies can realise green growth

The international configuration of manufacturing of several green industries has changed in the span of a few years. An increasing amount of green technology manufacturing has shifted to East Asian economies, particularly in the solar and wind industries. By 2010, Chinese producers accounted for over 50% of the global supply for solar PV and wind technologies (Liebreich, 2011). This radical increase in manufacturing supply has led to the plummet of global technological prices, thus making it increasingly difficult for firms located in states with higher production costs to compete. Between 2008 and 2012, prices for solar PV modules decreased by 80% whilst onshore wind turbines decreased by 29% (Liebreich, 2013). For green growth policy-makers, the challenge is to consider how to make domestic green industries resilient to global competition.

One potential solution for policy-makers is to institute policies that favour the domestic industrial base. These policies can include increasing import barriers, or imposing local content rules for technologies. In the case of the solar PV industry, manufacturing coalitions in the United States and EU have lodged anti-competitive cases against Chinese solar PV manufacturers (Zindler, 2012). The combination of low global prices and tariffs against their modules has led to increased distress amongst Chinese solar PV companies (Chase, 2013). It is acknowledged that like solar PV companies in the West, there will be major consolidations happening in the Chinese solar industry (Chase, 2013). These dynamics raise key political economy issues of the salience in investing in green industrial policy if it does not actually lead to green growth for the domestic economy.

Current environmental policy literature addresses this political economy issue by using different measures of innovation – particularly patents– to identify which countries can innovate green technologies (Dechezleprêtre & Sato, 2014; Johnstone et al., 2009). Environmental policy literature also evaluates the success of environmental policy instruments in stimulating green innovation (Ambec et al., 2013; Lanoie et al., 2011). These literatures are useful in terms of making comparisons between countries, especially with regards to the levels of technological capabilities. However this literature is less adept at addressing the political economy concern of whether having high technological capabilities is sufficient in appropriating the economic benefits of innovating technologies in the long-run.

This question arises as countries with lower technological capabilities transfer these technologies to build their own industrial capacity (Fu & Zhang, 2011; Lewis & Wiser, 2007; Wu & Mathews, 2012; Zhou et al., 2012). The resulting increase in industrial capacity in these late-comer countries – particularly China – undermines the industrial capacity of countries that first commercialised these technologies (Barua et al., 2012; Dutz & Sharma, 2012). First-mover economies' industrial capacity becomes threatened by the increase in production volume of green technologies either directly (through imports of cheaper technologies) or indirectly (by depressing global market prices for these technologies) (BNEF, 2014). Certain sets of academic literature suggest that latecomers' appropriation of global markets demonstrates the relevance of latecomer advantage over first-mover advantage (Mathews, 2013; Nahm & Steinfeld, 2013; Wu & Mathews, 2012). However this literature also ignores how the margins of economic value from manufacturing these technologies also decrease with the increase in global volumes – thereby limiting long-term growth opportunities. Therefore though latecomer advantage does enable these countries to enter these industries to realise green growth through manufacturing these technologies – it does not make these economies immune to global supply and demand dynamics.

Another set of literature thus becomes useful in taking an in-depth look at how various countries develop national innovation systems (NIS) to commercialise the next generation of technologies, or engage with innovations that reduce production costs (Buen, 2006; Foxon et al., 2005; Lo et al., 2013; Tang & Hussler, 2011). Both of these innovative activities can improve the competitive positioning growth opportunities of these economies (Maskell & Malmberg, 1999). Nevertheless the in-depth focus on individual countries – or a set of countries within the same category– does not enable direct comparisons between first-mover and late-comer countries. In surveying the empirical literature on both first-mover and late-comer countries' innovation systems for green technologies, a striking difference appears on the emphasis on having access to domestic markets versus access to domestic manufacturing. NIS of first-movers stresses the importance of demand policies and strategic niche markets (SNM) to enable the commercialisation of technologies (Foxon & Pearson, 2008; Schot & Geels, 2008; Verbong, Geels, & Raven, 2008). SNM were especially important in creating user-producer feedbacks to improve technology design and integration into broader market infrastructures (Geels & Raven, 2006; Kamp et al., 2004). The importance of user-producer linkages to enable increased technological capabilities is already quite well-developed within

NIS and international development literature (D'Costa, 2012; Henderson et al., 2002; Lewis & Wiser, 2007).

However the literature on late-comers emphasise the importance of having access to manufacturing facilities to enable technological learning (Atkinson et al., 2009; Mathews & Cho, 2000; Nahm & Steinfeld, 2013). Domestic firms increase RD&D efforts, whilst also partnering with both domestic and foreign research actors to undertake innovation (Fan & Hu, 2007; Lazonick, 2004; Tang & Hussler, 2011). If having access to domestic industry is important to enable technological learning, how does the shift – or at least, diminished size – of domestic manufacturing affect first-movers' opportunities to engage in similar kinds of technological learning?

This thesis thus seeks to address certain conceptual gaps in the current literature on green growth. First, it explicitly recognises that green industrial policy is subject to domestic political economy expectations. More specifically, states are interested in ensuring that public investments from green technologies are maximised within the local economy to realise green growth. However the ability for late-comers to appropriate market shares in green technologies appears to undermine the importance of innovation – an outcome that studies on green innovation do not fully address. This thesis argues that late-comers appropriation of global market shares does not necessarily signal long-run economic growth if the margins of technologies decrease with increased production volumes. In fact, it also leaves these economies to be vulnerable to global oversupply. Therefore it recognises that value-added from manufacturing changes over time as global production increases – another aspect that is under-appreciated in the current literature. Therefore the main conceptual gap is to understand why industrial activities shift across national borders at different stages of a technologies maturity – and the implications on green growth opportunities for different economies.

These conceptual gaps and questions are best addressed through using literature from EEG. EEG is a useful literature as it considers how the spatial relationship between innovation, manufacturing and markets changes over the course of a technology's development (Boschma & Frenken, 2006). Through analysing the spatial product life cycle (PLC), it demonstrates how these industrial activities locate in economies where comparative advantage exists (Vernon, 1966). These spatial dynamics ffect how different economies can realise economic growth, and highlights how much value-added these economies can receive based on understanding which economies compete in the different industrial activities (Amin & Thrift, 1992; Hassink, 2010; Pike, Dawley, & Tomaney, 2010).Therefore EEG is especially useful in redressing first-mover versus latecomer advantage through using the concept of resilience (Christopherson, Michie, & Tyler, 2010). This concept recognises how the spatial characteristics of technologies and industrial activities affect economies' exposure to competition in innovation and manufacturing. Through this framework, EEG emphasises why it is important for both academic literature and policy-makers to understand the spatial and temporal dynamics of different green technologies. These spatial dynamics have implication on both short and long-term opportunities for green growth in different economies.

1.2.3 Second aim: Do domestic economies need domestic manufacturing to sustain domestic innovation efforts?

Whilst EEG generally argues that both innovation and manufacturing activities can be spatially distant after commercialisation of technologies, this literature does argue that the relationships between these two activities are much more spatially proximate prior to commercialisation (Asheim, Coenen, & Vang, 2007; Audretsch & Feldman, 1996; Storper, 1997). This literature argues that the spatial proximity between these activities is needed to enable continuous interactive learning in testing new technologies; and to establish trust amongst partner actors in order to restrict knowledge spillovers with external actors (Storper & Venables, 2004).

The need for spatial proximity is also supported in the systems failure approach to innovation systems (Woolthuis et al., 2005). Innovation systems refer to how actors work within networks and institutional settings to engage with the process of innovation (Lundvall et al., 2002). These actors do not just include scientists and industrial firms, but entrepreneurs as well (Woolthuis et al., 2005). The systems failure approach argues that the failure of creating internal networks between innovative actors such as scientists, industrial actors and entrepreneurs leads to difficulties in "crossing the valley of death" (Markham et al., 2010). This analogy refers to when product innovations fail to achieve market commercialisation – thereby leaving these innovations on the shelf.

EEG recognises how certain innovation clusters – particularly neo-Marshallian districts – create specialised industrial districts that provides innovative actors access to domestic industry in order to engage in commercialisation activities (Amin & Thrift, 1992; Etzkowitz & Leydesdorff, 2000). In fact, industries tend to locate in these innovation clusters to also benefit from knowledge spillovers from University RD&D (Lee & Win, 2004; Østergaard, 2009). In fact, literature on the development of national systems of learning for late-comers economies emphasise the importance of having access to manufacturing facilities to enable technological learning (Fan, 2006; Lei et al., 2011; Mathews & Cho, 2000). Domestic firms increase RD&D efforts, whilst also partnering with both domestic and foreign research actors to undertake innovation.

What both of these literatures emphasise is the importance of spatial proximity in engaging in early stage commercialisation of technologies. Furthermore both of these literatures assume that innovative clusters have these industries within their own economy. Therefore if having access to domestic industry is important to enable technological learning, how does the shift – or at least, diminished size –of domestic manufacturing affect first-movers opportunities to engage in similar kinds of technological learning? The second aim thus considers whether economies engaged in the innovation of technologies do need access to domestic industry in order to engage in commercialisation activities.

1.3 Datasets used for the empirical research

The research will be undertaken through writing four different chapters, which are briefly outlined in the next section. This thesis uses the international solar PV industry as a case study to examine the spatial relationship between innovation and manufacturing over time. The three empirical chapters focus on applying the conceptual framework developed in Chapter 2 to examine the spatial dynamics of the global solar PV technologies. The conceptual framework argues that economies are resilient to global competition in supplying technologies when the industrial activities that it undertakes are less spatially mobile due to: (1) high transport and trade costs (thereby requiring innovation, manufacturing and markets to co-locate); and/or (2) the technologies that it produces are not replicable (i.e. no other economy has yet to learn how to manufacture these same technologies, enabling the firms in the first-mover economies to extract high economic rents).

The different technologies involved with solar PV technologies fall within a range of these spatial characteristics. The dominant technology (crystalline PV technologies) is spatially mobile and highly replicable as different actors can buy production equipment to undertake manufacturing (Bazilian et al., 2012). Nevertheless this production equipment still requires high-level process innovations involved with improving the efficiencies of the entire manufacturing process, and improving the quality of technologies produced (Pew, 2013). These kinds of process innovations can provide high value-added to economies, as these technologies are less replicable and requires access to specialised knowledge in sciences and engineering. However there are alternative PV technologies to the dominant design that are less replicable, and can provide higher margins of economic value to economies that manage to successfully commercialise these technologies (Goodrich, James, & Woodhouse, 2011). These technologies thus demonstrate how various economies have different levels of resilience to globally competitive dynamics, depending on which industrial activities they specialise in.

Two of these chapters directly base their empirical analysis on international datasets representing both research (as a proxy for innovation levels, or level of technological capabilities) and manufacturing activities. The fifth chapter uses 15 qualitative interviews with actors associated with research institutes, universities and firms located in various countries. Whilst the next section will focus on how the different chapters will use the data for its analysis, this section will describe the data, including providing notes on its usefulness and limitations.

1.3.1 Datasets representing "innovation"

The novelty of this research is that it uses different types of innovation 'output' datasets in order to have a standardised way of comparing countries' innovation efforts. These datasets include peer-reviewed scientific publications, patents and best-in class data of the solar PV industry. The scientific publications were downloaded from two of the largest academic databases: the Scopus and Web of Science (WoS) databases. Identification of the relevant articles was based on searching for articles that included "solar photovoltaic", and only downloading articles from scientific and industrial journals. Using solar photovoltaic as a search term is effective because researchers that would like to publish scientific and industrial results on solar PV advances will first use this term to highlight its relevance to this technological community. Through using the bibliometrics data from the academic databases, the research could identify country affiliations either through individual author's address (in the case of Scopus), or institutional addresses (in the case of WoS). However as the bibliometrics information in both databases did not directly separate the country information from the addresses, the author spent several months cleaning the data to obtain the relevant country addresses for either the authors or institutions. Undertaking this endeavour was worthwhile, as it provides more robust analysis for Chapter 3 and Chapter 4 (Carvalho & Perkins, 2015; Carvalho, 2015a). It is especially important for Chapter 4, which undertakes global innovation network analysis that is based on the co-author country affiliations.

The patent data that were collected came from the European Worldwide Office of Patent Statistics database (PATSTAT). By using inventor and firms'[1] country addresses for patents, the author could then obtain comparative evidence of where more applied industrial research was occurring. The patent dataset only include granted patents, thereby enabling a level of quality insurance of the data. The patent datasets are useful in recognising innovation that is closer to commercial applications than scientific publications. This dataset does have reporting limitations because not only technologies will be patented.

The best-in class data refer to publications that identify the best performing solar PV technologies at the time of publication. The two publications that provide this data are from the National Renewable Energy Laboratory (NREL), based in Colorado, USA. The second one comes from the *Progress in Photovoltaics: Research and Applications* journal, which posts bi-annual publication of "Solar Efficiency Cell Tables". These sets of data are widely recognised within the global solar PV community as recording the highest confirmed efficiencies of solar PV cells and modules for the different generations of solar PV technologies for any given time period. However there are important biases for these data. First, they do not capture all product innovations, but only new solar PV technologies which displace previous highest confirmed efficiencies, together with details of the inventor/fabricator. Furthermore, they only record product innovations which are sent to leading laboratories (in the US, Germany, Australia, Switzerland and Japan) for testing on a standardised basis, and therefore inevitably under-report innovation of the actual level of product innovations (e.g. innovations which

[1]The PATSTAT databases provided the Bureau Van Dijk Identification (BVD ID) numbers that could then be used to cross-reference with the Orbis database – which then provides the addresses of corporate headquarters of companies. The corporate headquarters were used as firm's addresses.

improve the durability of modules). Therefore, we cannot entirely rule out the possibility of systematic bias across countries, although the prestige of being a recognised front-runner means that leading research institutes have motives to disclose results in order to attract – or even sustain – research funding. We also reduce the risk of country bias by using two datasets assembled and published in two different countries. It should be noted that best-in class data are only used for Chapter 3's analysis.

As each dataset has some limitations, Chapter 3 and Chapter 4 consider all the datasets as a way of triangulating the results in terms of comparative significance of countries' contribution to global innovation efforts. Furthermore each type of research dataset (scientific publications, patents and best-in class) has at least two different 'sources' that also try to confirm the different proportions of countries. Therefore though the thesis research does treat the findings from this analysis as preliminary, it has taken every effort to use the multiple data sources to cross-reference the interpretation of the results.

1.3.2 Datasets representing manufacturing and industrial capacity

The manufacturing dataset is derived from Bloomberg New Energy Finance (BNEF) data that have confirmed manufacturing capacity of countries in different parts of the crystalline PV supply chain. While capacity and output production will not be perfectly correlated, capacity data nevertheless provide us with a comparative measure of the importance of different countries as producers of solar PV. Unfortunately this dataset does not have manufacturing capacity for alternatives PV technologies that can compete with crystalline PV technologies. Nevertheless it is confirmed that these alternative technologies account for less than 5% of global solar PV manufacturing capacity (Chase, 2013). Therefore in calculating different countries' proportion of global manufacturing capacity, the exclusion of this capacity is negligible. Furthermore through industrial reports, the research can confirm that countries that successfully manufacture and sell these technologies have manufacturing plants located in USA, Japan and to a much smaller extent, China (Chase, 2013; Goodrich et al., 2011; Pew, 2013).

Another limitation of the current manufacturing dataset is that it does not provide data on manufacturing capacity of production equipment for solar PV technologies. This production equipment refers to the technologies that are installed in solar PV factories to manufacture the actual solar PV technologies (de la Tour, Glachant, & Ménière, 2011). Having this dataset would provide a better understanding of the entire value chain within the solar PV industry. Instead the research relies on other third-party verification from BNEF reports to identify which economies manufacture these technologies (primarily, the USA, Germany, Switzerland, and more recently, China) (Chase, 2013). However consideration of both alternative and production equipment is considered in the analysis of Chapter 4 and 5. Nevertheless the manufacturing capacity in the solar PV value chain is still useful in showing key spatial dynamics for Chapter 3, which is the only chapter in which manufacturing capacity is directly used for comparative analysis amongst countries.

1.3.3 Qualitative interviews

The datasets outlined above are useful in providing analysis at the international level. However the thesis research was also interested in getting more micro-analysis on the spatial relationship between innovation and manufacturing. This kind of analysis is especially important for understanding the nature of collaborations between researchers and industrial firms. Whilst research publications and patents are useful in terms of showing 'codified' output results of spatial patterns of collaborations, EEG recognises that significant part of knowledge spillovers occurs through tacit exchanges amongst different actors.

Whilst it is impossible to interview all the actors within solar PV research networks, the research focused on identifying the main research institutes involved with solar PV research. This information was identified through the best-in class datasets. Therefore the researcher contacted the head researcher of institutes, or Presidents/Vice Presidents of firms, to participate in interviews. Furthermore the researcher attended solar PV industrial conferences in China and the United Kingdom (UK) to speak to potential participants. The researcher ended up with 15 in-depth interviews with participants that were associated with institutional affiliations in Australia, China, Germany, Netherlands, Switzerland, UK, and the United States of America (USA). These interviews were either taken in-person (in the UK and China), or over Skype and emailed answers. It would especially be beneficial to extend the analysis by interviewing more participants – especially from Japan, Singapore, Canada and the USA. Nevertheless these interviews were especially useful in identify how countries with small domestic solar PV industries – such as Australia, Netherlands, and the UK – still play an important role in the research for solar PV technologies. The insights from these countries present novel findings on the kinds of collaborative strategies these countries take with foreign industrial partners.

Table 1. Information on data measures and sources

Industrial activity	Data Source	Time period	Additional notes
Manufacturing: Manufacturing capacity of PV modules (Megawatt [MW] capacity)	Bloomberg New Energy Finance (BNEF)	2005-06.2012	1. Annual data on manufacturing capacity for selected countries. Capacity is used as an indicator of the relative size of manufacturing output. 2. BNEF also provides capacities for tier 1 and 2 silicon and solar PV cells.
Research innovation: Scientific publications	Scopus (Elseiver)	Restricted to 1990-2012	1. Relevant publications identified using search term, "solar PV".
Research innovation: Scientific publications	Web-of-Science (Thomson Reuters)	Restricted to 1990-2012	1. Relevant publications identified using search term, "solar PV".
Innovation: Patent filings (absolute numbers)	European Worldwide Office of Patent Statistics	Restricted to 1990 -2012	1. Countries identified using reported addresses of inventors and firm (Bureau van Dijk Identification) BVDID addresses. 2. Solar PV patents identified using patent classification code, "Y02E10". 3. Only patents granted included in the dataset, yielding 51,293 patents.

Industrial activity	Data Source	Time period	Additional notes
Product innovation: PV cell data (absolute numbers)	National Renewable Energy Laboratory (NREL)	1976-09.2013	1. Total of 205 data points for different PV cells. 2. NREL categorises them within 24 types of PV cells, which are classified in 5 broad family classes. 3. The locations where PV cells were developed verified by additional research.
Product innovation: PV cell data (absolute numbers)	Solar cell efficiency tables from *Journal of Progress in Photovoltaics*	1997-2012	1. Total of 208 data points for both PV cell and modules. 2. Similar type/family classification to NREL. 3. Location where PV cells were developed verified by additional research. 4. Due to limited data availability, the first time period is between 1997 and 2004, and second 2005-2012.
Research and manufacturing: interviews with participants affiliated with research institutes and technological firms (both production equipment and final product firms)	15 interviews with actors directly affiliated with institutions in Australia, China, Germany, Netherlands, Switzerland, UK, and the USA	Interviews conducted between 2013-2014.	1. Both institutional and country affiliations are not attributed to any quotes, unless permission has already been granted. 2. Importance of anonymity is because participants would be easily identifiable, even with the country affiliations.

Source: Author's compilation

1.4 Research chapters

1.4.1 Chapter 2. Reconsidering green industrial policy: Does techno-nationalism maximise green growth in the domestic economy?

This chapter recognises how techno-national debates on green industrial policy are connected to domestic political economy expectations of green growth (Barua et al., 2012; Karp & Stevenson, 2012). Techno-nationalist policies are aimed at ensuring that the returns from green industrial policy are appropriated within the national economy. The domestic political economy debate focuses on whether it is worth supporting green innovation and markets if other economies learn to manufacture and export these technologies (Bell & Pavitt, 1997). The literature on green growth recognises that global competition results in innovation and manufacturing shifting to countries where comparative advantage exists (Hallegatte et al., 2011; OECD, 2011), but these spatial dynamics contradict the political economy expectations of economic spillovers between domestic innovation, manufacturing and markets.

This chapter focuses on how this techno-nationalist perspective is problematic. In doing so, it develops a conceptual framework based on the spatial characteristics of industrial activities and technologies. This spatial perspective is derived from key theories from EEG literature – particularly the spatial PLC and economic resilience. Through this spatial framework, it demonstrates how different economies are exposed to global competition and examines how innovation enables economies to become resilient to global competition in manufacturing. Lastly it illustrates how supply-side protectionism can inhibit domestic market expansion along with associated economic value and employment opportunities. Consequently, the chapter seeks to provide a balanced assessment of how domestic economies can achieve green growth from innovation, manufacturing and markets.

As such, this chapter seeks to fulfil the first aim of this thesis by demonstrating how a spatial perspective on technologies is helpful in explaining internationally competitive dynamics and the implications on domestic green growth opportunities. This framework is also useful in differentiating green technologies according to their characteristics of: (1) spatial mobility (based on transport and trade costs); and (2) production replicability – that is, ability for other economies to also manufacture these technologies. These spatial dynamics thereby influence the relative spatial distances between research, manufacturing, and markets.

Furthermore these spatial dynamics can help explain the resilience of domestic economies to global competition in supplying these technologies.

1.4.2 Chapter 3. First-mover advantage and the spatial evolution of innovation and manufacturing in the solar PV industry

Within the context of debates about the resilience of first-mover advantage (FMA) in 'clean tech', this chapter explores the changing spatial distribution of economic activity in the global solar PV industry. Conceptually, we situate our analysis in the spatial PLC model, which gives rise to two hypotheses (Boschma & Frenken, 2006; Vernon, 1966). The spatial decoupling hypothesis posits that there will be a spatial separation between innovation and manufacturing over time, with first-movers retaining competitive advantages in innovation (Audretsch & Feldman, 1996); while the spatial recoupling hypothesis suggests that innovation will eventually follow manufacturing as it migrates to late-comers (Mathews & Cho, 2000).

This research takes a macro-level perspective in seeing how different first-mover and late-comer countries account for different levels of innovation and manufacturing activities during two different time periods. The results show that whilst there has been a major shift of manufacturing capacity to late-comers (notably China), the research finds only partial evidence of recoupling, at least when measuring innovation by patents or countries' production of best-in-class solar cells. Using scientific research publications provides a slightly different picture, suggesting that late-comers are increasingly catching up with first-movers. The chapter concludes by discussing the relevance of the findings for debates about the importance of proximity for innovation and policy-inducted FMA.

The results from Chapter 3 highlight can address both the research aims of this thesis. First it demonstrates how EEG concept of spatial PLCs is useful in assessing the competitiveness debate between first-mover and latecomer countries. Second it provides a discussion of whether increases in industrial capacity also are relevant for inducing – or sustaining – innovation.

1.4.3 Chapter 4. Accessing knowledge spillovers through international research collaborations: Analysis of solar PV innovation networks

The structure of global innovation networks (GINS) and international research collaborations can highlight the level and quality of knowledge spillovers different countries have – based on their position within these networks and the countries they actually collaborate with. EEG and international development literature implicitly recognises that a hierarchy exists amongst countries with different levels of technological capabilities. Countries with high technological capabilities are those that can engage with innovation at the technological frontier – and can thus restrict international research collaborations between these select groups of countries. International development literature recognises that countries with lower technological capabilities undertake research collaborations with countries with high technological capabilities in order to benefit from experiential and knowledge spillovers. However both of these literatures acknowledge that the 'catch up' nature of these collaborations does not necessarily guarantee that countries will benefit from knowledge spillovers at the technological frontier.

This chapter explores these interactions by studying the evolution of different countries positions within different solar PV innovation networks over two time periods. It also focuses on the research collaboration profiles of Germany, Japan and USA (as first-mover countries) and China (as a late-comer). The preliminary results have some surprising findings on how countries with high technological capabilities but low industrial capacity play a more prominent role in research collaborations for each of these countries with large industrial capacity. The chapter considers whether competitive dynamics of domestic industries influences the patterns of international research collaborations. As such, it considers how the size of the domestic industry can potentially affect patterns of international research collaboration due to techno-national considerations. However it highlights a potentially important role that countries with low industrial capacity but high technology capabilities play for countries with large industrial capacities.

1.4.4 Chapter 5. How does the presence – or absence – of domestic industries affect the commercialisation of technologies?

Literature in EEG highlights the importance of the spatial proximity between research institutes and industrial firms in facilitating learning feedback between these different types of actors when engaging in commercialisation for early stage technology. This literature assumes the existence of domestic industries to enable these commercialisation efforts. This chapter considers the importance of domestic industry in enabling innovation efforts for different solar PV technologies. It does so by comparing the responses of interviewees who are involved in different types of solar PV technologies, and are based in economies that have different sizes of solar PV industrial capacity. These economies include Australia, China, Germany, Netherlands, Switzerland, and the USA.

The research highlights how the professionalisation of solar PV sciences and the spread of solar PV social networks have enabled innovators and industrial actors to 'search for the right partners' in early-stage research for alternative PV technologies. While there is no guarantee, the presence of domestic industries with diverse skill sets can increase the probability of finding a partner with the right knowledge complementarities. These preliminary findings also illustrate how strong linkages between research institutes and domestic industries can intentionally limit international knowledge spillovers that can help foreign industrial partners to compete with domestic industries. In contrast, the absence of domestic industrial linkages incentivises research institutes to seek foreign industrial partners for commercial collaborations.

Therefore the research findings identify key nuances in the spatial relationship between innovation and manufacturing, thereby addressing both aims of the thesis. First, it demonstrates that countries with high technological capabilities do not necessarily need access to domestic industries to engage with commercialisation efforts. Instead these economies can undertake linkages with foreign partners that have high industrial capacities. This conclusion provides evidence that the spatial relationship between innovation and manufacturing can be spatially distant in the next cycle of technologies. Second, it highlights how techno-national factors can affect the propensity for international research collaborations to occur between countries with different industrial capacities – a factor not discussed in the current EEG literature.

1.5 Conclusion

This thesis thus seeks to understand how the spatial relationship between innovation and manufacturing changes over time, and how it affects the level of economic value-added to different economies participating in these industries. This spatial perspective will be useful to green growth literature that is considering how to assess the competitiveness of economies in supplying green technologies. The motivation for using this perspective arises as it appears that the opportunities to realise green growth in the domestic economy are threatened as more economies compete to supply green technologies. Current green growth literature primarily focuses on innovation activities to determine which economies will innovate new green technologies. However success in innovation does not necessarily guarantee that manufacturing for these technologies will remain in the same economy.

Therefore this thesis examines the spatial dynamics between innovation and manufacturing as the primary unit of analysis. The research seeks to understand why these industrial activities locate in various types of economies as technologies mature – and its implication on level of green growth for these economies. In studying this relationship, it considers whether economies do need access to domestic industries in order to up-scale new product innovations or engage with high level process innovations. Rather than study this spatial relationship within individual economies, this research compares economies that first undertook indigenous innovation with those that industrialized via technological catch up. These spatial dynamics can provide a balanced assessment of whether green growth in the domestic economy will be realised from domestic supply and/or domestic markets for green technologies.

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Chapter 2: Reconsidering green industrial policy: Does techno-nationalism maximise green growth in the domestic economy?

Addressing political economy concerns of investing in green industrial policy by applying insights from evolutionary economic geography

Abstract. This chapter recognises how techno-national debates on green industrial policy are connected to domestic political economy expectations of green growth. Techno-nationalist policies are aimed at ensuring that the returns from green industrial policy are appropriated within the *national* economy. The domestic political economy debate focuses on whether it is worth supporting green innovation and markets if other economies learn to manufacture and export these technologies. The literature on green growth recognises that global competition results in innovation and manufacturing shifting to countries where comparative advantage exists, but these spatial dynamics contradict the political economy expectations of economic spillovers between *domestic* innovation, manufacturing and markets. This chapter focuses on how this techno-nationalist perspective is problematic. In doing so, it develops a conceptual framework based on the spatial characteristics of industrial activities and technologies. Through this spatial framework, it demonstrates how different economies are exposed to global competition and examines how innovation enables economies to become resilient to global competition in manufacturing. Lastly it illustrates how supply-side protectionism can inhibit domestic market expansion along with associated economic value and employment opportunities. Consequently, the chapter seeks to provide a balanced assessment of how domestic economies can achieve green growth from innovation, manufacturing and markets.

2.1 Introduction

Beyond the environmental imperative, the political justification for green industrial policy includes economic and social benefits that can be realised within the national economy

(Hallegatte et al., 2011). These co-benefits consist of improving domestic companies' profitability and building domestic green industries to increase net employment (Jacobs, 2012). Therefore policy support and fiscal investments into green industrial policy can yield green growth in the national economy (Bowen et al., 2009). This economic rationale was used by national governments to support green stimulus packages after the start of 2008/09 economic crisis (Barbier, 2010). Out of a total of USD 2.8 trillion in stimulus packages globally, 16% was dedicated specifically to green sectors (Robins, Clover & Singh, 2009, p. 2). Nevertheless the opportunity to realise green growth in each national economy appears to be threatened as more economies compete to supply green technologies (Barua, Tawney & Weischer, 2012).

The current literature on these competitive dynamics analyse the merits of first-mover versus late-comer advantage. The early literature demonstrates how certain developed economies were successful in developing green technologies through policies establishing national innovation systems (Bergek et al., 2008). The Porter hypothesis confirmed that early success in the commercialisation of green technologies enabled economies to achieve first-mover advantage in global markets (Porter & van Der Linde, 1995). However, the rise of Chinese, Taiwanese and Indian solar photovoltaic (PV) firms and wind technology companies challenges the merits of first-mover advantage (Lewis & Wiser, 2007; Liebreich, 2011). These firms' success in manufacturing resulted from technology transfer and capitalising on their comparative advantage in low-cost production (Lewis & Wiser, 2007; Wu & Mathews, 2012).

These international dynamics have stimulated techno-national debates similar to those that occurred with other technologies such as internet and communication technologies (ICT), and electronics. Archibugi & Michie (1997, p. 17) highlight how techno-nationalist perspectives can affect public attitudes towards industrial policy: "What is the point of government policies to promote innovation in industry if the benefits can be transferred to other countries? Is there any guarantee that firms will use these benefits to the advantage of the nation which provides support?" This chapter argues that these political economy concerns centre on whether the domestic economy can appropriate the returns from public investments into green industries.

These debates on green growth can benefit from evolutionary economic geography (EEG) theory, which addresses how global dynamics of technological competition affects local economic development (Potter & Watts, 2010). More recent literature on green growth recognises that innovation and manufacturing of green technologies shift to countries where comparative advantage exists (Dutz & Sharma, 2012). For example, international organisations such as the recently established Global Green Growth Institute identify how various economies can realise green growth (Barua et al., 2012; OECD, 2011b). However this literature does not recognise how globally competitive dynamics affect long-run economic returns from industrial activities. Therefore EEG demonstrates how the concept of 'resilience' identifies key opportunities and challenges facing economies in realising green growth in the long-run. The second gap in the literature on green technologies is that it does not differentiate technologies according to their spatial characteristics. However these characteristics influence the balance of economic value from technology supply and market creation. This chapter argues that protectionist policies towards supply-side firms can incur opportunity costs from not realising green growth or providing domestic employment through market expansion.

This chapter's objective is to address techno-national concerns regarding investment in green industrial policy. To this end, the second section of the chapter demonstrates how the lack of a spatial perspective on technologies in the current literature creates dilemmas in the political economy. The third section draws on EEG's concept of resilience to demonstrate long-term green growth opportunities for different economies. The fourth section considers how spatial characteristics of technologies affect the balance of growth from supply and demand for green technologies in the domestic economy. The last section reviews how this spatial perspective is useful for the literature on green growth, and considers questions for future research.

2.1.1 Realising green growth through green industrial policy

2.1.2 Key premises of green growth

Green growth stems from a combination of sustainable development, ecological modernisation, and endogenous economic growth imperatives (Hepburn & Bowen, 2012). The analysis of green growth is largely circumscribed by environmental economics and policy fields – and now increasingly, the industrial policy sphere (Rodrik, 2013). The rationale for green growth is described in the literature according to three underlying premises (Hallegatte et al., 2011; Jacobs, 2012):

1. There is a need to sustainably preserve natural capital in the process of economic development.
2. Innovation (both technological and organisational) can be used to significantly decrease the impact on the environment.
3. Such innovation can provide long-run economic growth opportunities through improving production efficiencies, whilst creating new industries and markets.

The first two premises have strong ideological underpinnings in sustainable development and ecological modernisation. Their combined argument is that economic growth can be decoupled from long-term environmental impacts through developing green technologies (Coenen & Díaz López, 2010). Bailey & Wilson (2009) recognise how these premises of green growth are in line with the hegemonic discourse of neoliberal techno-centric solutions to environmental problems. They are techno-centric by focusing on technological innovation as a solution to environmental problems, and neoliberal because of the emphasis on, "economic growth as the normal condition of a healthy society" (Dryzek, 1997, p. 46). Premises of green growth are in direct contrast to green radicalism, which places a greater inherent value on the environment over the imperative of economic growth. Its main critique is that the pursuit of economic growth is misaligned with the goal of maximising the welfare of both society and the environment (Meadows, Meadows & Randers, 2004). Instead, environmental policy should focus on the importance of social and economic values to create behavioural changes that preserve the ecological rather than the capitalist system (Fitzpatrick, 2011). These critiques are especially important in terms of questioning the viability of substituting natural capital with green technological capital (Neumayer, 2003).

The green radical perspective is useful in questioning whether technological solutions will be deployed in time to avoid irreversible climate change. Solar PV and wind technologies demonstrate how clean energy technologies can make significant technological advances over a short period of time and become cost-competitive with incumbent technologies (see Figure 10). However, other low-carbon technologies still need to move along the learning curve to provide more low-carbon energy alternatives. The IEA estimates that energy and process-related emissions have to reduce to half the 2011 level by 2050 in order to avoid a 2 degree Celsius increase in global average temperatures (IEA, 2014).

2.1.3 Techno-national debates and green industrial policy

Nevertheless this chapter's critique of the current literature on green growth focuses on the lack of spatial analysis underlying the third premise of endogenous economic growth brought about by green innovation. The dual challenges of the economic recession in 2008/2009 and the on-going international negotiations on resolving climate change created 'windows of opportunity' for directing fiscal stimulus investment into green industries (Barbier, 2010; Bowen et al., 2009). It is believed that targeted public investments, supported by green industrial policies, will help economies achieve a green industrial revolution and 'long-waves of economic growth' (Stern & Rydge, 2013). The economic rationale of this third premise provides a strategic and analytical case for politically justifying green industrial policy beyond a concern for the environment (Bowen & Fankhauser, 2011).

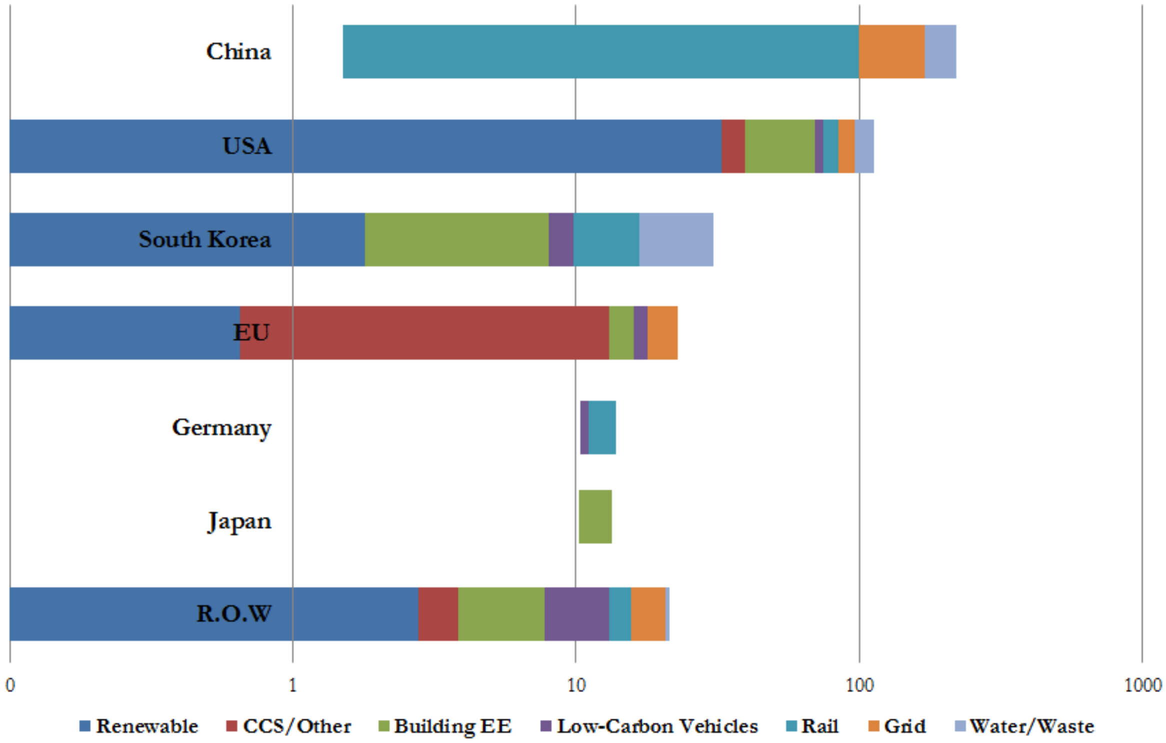
This chapter argues that the early literature underappreciates the spatial implications of green growth – thereby creating controversies over green industrial policies in the domestic political economy. The third premise of green growth does not consider whether public investments in domestic green industries will yield economic spillovers to the local economy. This lack of spatial analysis creates an inherent domestic political economy expectation that public investments into Research and Development (R&D), industry and markets will benefit domestic actors. However the ascendency of Chinese solar PV firms encroaching on American and European market shares highlights key domestic political economy problems in not addressing these spatial expectations. For example, public investments that support domestic markets are not necessarily met by technologies manufactured within the local economy. When there are low trade barriers, market demand can be met by low-cost technologies manufactured in foreign economies. Between 1999 and 2011, China increased its share of global production of solar PV technologies from 1% to over 60% (UNEP & BNEF, 2010; Wang, 2013). These low-cost imports make it more difficult for manufacturing plants in economies with high production costs to compete (Chase, 2013; Zindler, 2012).

Intensified global competition in the supply of technologies has resulted in international trade disputes. In the case of solar and wind, global price reductions created economic distress for American and European solar PV firms (see Figure 3 and 4 in Section 3). American solar- and wind manufacturing coalitions successfully lobbied the US government to impose tariffs against imports of Chinese technologies and Vietnamese (wind) technologies in 2012 (Zindler, 2012), and in 2013 the EU imposed import tariffs on Chinese solar technologies (EU Commission, 2013). It should be noted that the justification for tariffs was unfair competition due to generous subsidies in the form of low-interest loans Chinese firms. China reacted by imposing anti-dumping tariffs in 2013 against US and South Korean polysilicon imports (Hook, 2013). Another 'green' trade dispute over Brazilian ethanol exports to American markets ended in 2011 (Winter, 2012).

These developments demonstrate that domestic policy-makers do react to global competitive dynamics – especially when it threatens domestic industry. In the case of trade disputes, these political economy frictions occur as domestic public investments go towards market-based subsidies for green technologies. The policy rationale for these market subsidies is to help green technologies overcome cost-differentiation with low-cost incumbent technologies (Hallegatte et al., 2011). However an inherent political economy perception is that domestic supply-side actors should benefit from this subsidy – not just in terms of engendering learning economies but in appropriating market share. As Karp & Stevenson (2012, p. 5) explain with regard to the American political economy stance on Brazilian ethanol: "To prevent Brazilian exporters from undercutting US producers, and sending US tax dollars to Brazil, the US imposed a near-prohibitive tariff on ethanol imports until the end of 2011, when the subsidy lapsed."

Now that governments in both developed and emerging economies are investing in green industrial policies for both the supply and demand of different green technologies (see Figure 1 below), there is global competition for supplying green technologies to multiple markets. Other countries' success in innovation and manufacturing can potentially limit future avenues for green growth within the local economy (Archibugi & Michie, 1997). Techno-national debates occur when it appears that domestic investments to support the development of green technologies will not benefit the domestic economy in the long term (Karp & Stevenson, 2012; Lewis, 2012). These outcomes go against the domestic political economy expectation of appropriating returns from public investments in the national economy (Archibugi & Michie, 1997).

Figure 1. Dedicated funds to green sectors from national Economic Stimulus Packages 2008/2009 (Total Estimated Investment in Green Sectors = USD 435.9 billion)



Source: Data derived from (Robins et al., 2009, p. 2)
** Note: x-axis is on a base 10 logarithmic scale*
**Note: R.O.W: refers to the "rest of the world".*

Green technologies are one of the latest industries to undergo techno-national debates. Other industries include space, automobiles, and currently, internet and communication technologies (ICT) (Dicken, 2011). For ICT technologies, the main debates centre on developing international standards for intellectual property rights (IPR) to enable technology transfer, and national security concerns over providing foreign firms access to domestic markets (Ernst, 2009). Techno-national debates of green technologies have a similar concern over protection of IPR to protect domestic investments in R&D, and providing domestic market access to foreign firms (Karp & Stevenson, 2012; Lewis, 2012; Ockwell et al., 2010). However these techno-national debates are compounded by political economy controversies related to environmental policies. These include continued scepticism regarding the climate change phenomenon and the imposition of stringent environmental policies (Fitzpatrick, 2011). The latter becomes particularly salient if the political economy perceives the costs of environmental compliance as a threat to the competitiveness of industries exposed to foreign competition (Dechezleprêtre & Sato, 2014).

Further political economy inertia in diffusing green technologies involves techno-institutional 'lock-in' effects of incumbent, 'brown' technologies (Foxon & Pearson, 2008). These effects refer to complimentary network infrastructures and institutional support (including organised political lobbying) of incumbent technologies. Verbong & Geels (2007) demonstrate how the ease of integration of biomass into fossil-fuel power plants in the Netherlands enabled biomass energy to have greater diffusion than solar PV and wind technologies. Moreover, lock-in to the supply or dependence on fossil fuels can reinforce resistance to green technologies (and incur even higher switching costs) (Unruh, 2002). These lock-in effects demonstrate the additional costs of modifying physical and policy infrastructures, the inflexibility of user behaviours and the power of industrial lobbying (Barbier, 2010; Hallegatte et al., 2011; Stern & Rydge, 2013). These controversies can compound techno-national debates on the perceived costs of transitioning to a green economy.

However, the Porter hypothesis demonstrates that green technologies offer 'win-win' economic growth opportunities that could counteract their political resistance. The Porter hypothesis argues that the early imposition of stringent environmental legislation would create incentives for polluting firms to innovate green technologies (Porter & van Der Linde, 1995). Green innovations would improve the competitiveness of domestic firms through productivity improvements that also reduce environmental compliance costs. Their success in the early commercialisation of green technologies would create first-mover advantages when selling these technologies to foreign markets. Empirical studies by Johnstone et al. (2009, 2010), Lanoie et al. (2011), and Newell, Jaffe & Stavins (1999) do show increases in R&D expenditures and/or patenting in less environmentally-intensive technologies after the imposition of environmental policies. Nevertheless, there are mixed results on whether these innovation efforts improved production efficiencies and economic competitiveness (see overview by Ambec et al., 2013).

Noailly & Shestalova (2013) and Fankhauser et al. (2013) demonstrate the importance of knowledge complementarities in enabling countries' to develop different green technologies. For example, improved scrubber systems can be used to reduce particulates from fossil-fuel electricity generation plants. However a fossil-fuel plant will not innovate a renewable technology as it does not have the necessary knowledge base. Furthermore Aghion et al. (2012) demonstrates how countries with previous experience in green innovation are more likely to be successful in subsequent innovation than countries who lack this experience, despite both countries facing similar punitive policies on pollution. Consequently, these studies show how both stringent environmental regulation and broader industrial policies are needed to enable the development of technologies (Foxon et al., 2005b; Goodward et al., 2011)

2.1.4 The internationalisation of green technologies: entering industries through indigenous innovation or manufacturing

Creating comprehensive green industrial policies are important in countries' pursuit of green growth (Rodrik, 2013; Schwarzer, 2013). Industrial policies involve a combination of technology-push policies – encouraging development and early commercialisation of new technologies – and demand-pull policies – creating a market demand to enable large-scale diffusion (Hallegatte et al., 2011; OECD, 2011b). The particular policy mix will be determined by various factors. The first factor is the technology's stage of development (Foxon et al., 2005a; Watson et al., 2014). Emerging green technologies such as wave- and tidal technologies, carbon capture and storage (CCS), and integrated combined cycle combustion, being at the R&D and demonstration project stage, are better supported by supply-side policies in the form of technological grants and R&D tax breaks to innovating firms. On the other hand, on-shore wind and crystalline solar PV technologies, which are already in production, means industrial policy focuses on overcoming barriers in integrating these technologies into existing power infrastructures (Woolthuis, Lankhuizen & Gilsing, 2005).

Another factor influencing policy instrument choice is the institutional preference of domestic economies. Foxon et al. (2005) shows that the UK's preference for market-based instruments led the initial use of renewable obligations to create demand for wind technologies. In contrast, Denmark and Germany successfully used feed-in tariffs for the early commercialisation of small-size wind turbines (Klaassen et al., 2005). Both of these studies, along with Woodman & Mitchell (2011), argue that the early success of wind turbine development in Germany and Denmark over the UK[2] was because their choice of

[2]The UK has reformed its demand-side approach to renewable technologies by replacing renewable obligation certificates with a contract-for-differences approach (a modified form of feed-in tariff) for utility-scale electricity generation (Woodman & Mitchell, 2011).

instrument provided a stable demand signal for domestic firms to invest in the production of these technologies. Another example is Brazil's biofuel blend mandates which encourage domestic ethanol production (Goldemberg et al., 2004). In the USA, the preference was for production and investment tax credits for wind technologies, but uncertainties over the renewal of tax credits after their expiry created major fluctuations in asset financing of projects (UNEP & BNEF, 2010, 2013).

These early demand-side signals were met by domestic supply due to the paucity of market-ready technologies. Most studies on technology-push policies of green technologies highlight the importance 'crossing the valley of death' in bringing potential innovations into early commercialisation (Canton, 2005). Goodward et al. (2011) demonstrate how public and private R&D for technologies, including direct funding or tax breaks to private firms, is essential for experimentation with different technological designs. Innovation studies also highlight the importance of creating learning feedback loops between producers of technologies and 'lead' users of technologies (Nill & Kemp, 2009). Raven & Geels' (2010) comparison of the Danish and Dutch biogas industries shows the importance of applied learning between research institutes, industries and users. These interactions in Denmark led to the success of biogas technology development, while insulated scientific learning in the Netherlands meant the Dutch industry's success was more limited. These same comparative findings between Denmark and the Netherlands are presented by Kamp, Smits & Andriesse (2004) for the wind industry. Musiolik & Markard (2011) demonstrate how government policies were used to create formal innovation networks between researchers and industry in Germany, enabling the successful development of fuel cell technologies. Watanabe et al. (2000) argue that the dynamism in Japan's solar PV industry was partly attributable to broad-based government policies, but more so to knowledge spillovers between industrial players.

Ultimately these studies demonstrate that the economies that were successful in diffusing green technologies were those that established strong national innovation systems (NIS) – a conceptual construct for analysing the development and diffusion of new technologies within a specific country by examining the interaction amongst actors, networks and institutions (Lundvall et al., 2002). However, these studies did not engage with how the development of the domestic industry was affected by global competition dynamics. At the time of early commercialisation, the lack of foreign suppliers of technologies meant global competition for domestic markets was limited.

Table 1. Top 10 global wind manufacturers in 2005 & 2010 (by production capacity)

2005			2010		
Company	Country	Production (GW)	Company	Country	Production (GW)
1. Vestas	Denmark	3.2	1. Vestas	Denmark	6.3
2. Enercon	Germany	2.7	2. GE Wind	USA	6.0
3. Gamesa	Spain	1.9	3. Sinovel	China	5.3
4. GE Wind	USA	1.3	4. Gamesa	Spain	4.4
5. Siemens	Germany	1.1	5. Goldwind	China	3.6
6. Suzlon	India	0.9	6. Suzlon	India	3.5
7. Repower	Germany	0.9	7. Enercon	Germany	3.4
8. Goldwind	China	0.7	8. Dongfang	China	3.0
9. Nordex	Germany	0.5	9. Repower	Germany	2.9
10. Ecotecnica	Spain	0.3	10. Siemens	Germany	2.9

Source: Liebreich (2011, p. 31)

Table 2. Top 10 global solar PV manufacturers in 2005 & 2010 (by production capacity)

2005			2010		
Company	Country	Production (GW)*	Company	Country	Production (GW)*
1. Sharp	Japan	500	1. JA Solar	China	1,900
2. Q-Cells	Germany	420	2. Suntech	China	1,620
3. Suntech	China	270	3. First Solar**	USA	1,502
4. Motech	Taiwan	240	4. Yingli	China	1,100
5. Solarworld	Germany	200	5. Trina Solar	China	1,000
6. China Sunergy	China	180	6. Q-Cells	Germany	1,000
7. Kyocera	Japan	180	7. Canadian Solar	China	800
8. Isofoton	Spain	130	8. Motech	Taiwan	600
9. Schott	Germany	121	9. Gintech	Taiwan	600
10. Sanyo Electric	Japan	115	10. JinkoSolar	China	600

Source: Liebreich (2011, p. 33)
**Production capacity is from BNEF research and is based on company announcements.*
***First Solar produces thin-film solar PV technologies, whereas the other companies listed produce crystalline PV technologies.*

China's proportion of global manufacturing of solar PV and wind technologies has led to an increased focus on how it was able to up-scale production capacity for these technologies so quickly. The empirical literature acknowledges that China's entry into solar PV and wind technologies occurred when it was possible to transfer technologies. Wu & Mathews (2012) and de la Tour, Glachant & Ménière (2011) describe how both Taiwanese and Chinese firms bought the most advanced production equipment from suppliers in the USA and Germany.

This equipment allowed Chinese firms to quickly upscale production across the solar PV value chain. In contrast, China's entry into wind manufacturing relied more on a combination of indigenous innovation and technology transfer (Gosens & Lu, 2013; Lewis & Wiser, 2007). It was not possible to buy production equipment for wind technologies as the producers of the production equipment also competed in the manufacture of the final product (Pew, 2013).

These industries also benefitted from significant government support. De la Tour, Glachant & Ménière (2011), D'Costa (2012), Saxenian (2002), and Khanna (2008) describe how China and Taiwan instituted policies to draw their diaspora back home, bringing their expertise to develop domestic firms. These governments also subsidised loans for manufacturing facilities through state and national developmental banks (Goodrich, James & Woodhouse, 2011). Furthermore, they built infrastructure to support industrial districts for these technologies. However, these studies also note that this support was given at different levels of government in China due to differences in policy agendas (Bedin et al., 2013; Liu & Goldstein, 2013). Wind technologies had a combination of federal and provincial support that was aimed at meeting ambitious domestic market targets; the federal government recognised the large-scale potential of wind power to meet China's growing energy demand. In contrast, provincial governments in China pursued the development of solar PV industry as an export-oriented growth strategy (Zhang et al., 2013). Prior to the imposition of tariffs against Chinese solar PV products, about 95% of Chinese solar PV technologies were exported to foreign markets (UNEP & BNEF, 2011).

2.1.5 Re-examining techno-national debates on competitiveness and green growth

These international dynamics raise techno-national questions on green industrial policy. Should governments invest in the early commercialisation of green technologies if foreign economies can acquire these technologies to produce them at lower cost? Furthermore, should countries that engaged with early R&D ensure that technologies are not transferred to foreign economies? Lastly should foreign firms be able to sell to domestic green markets if it undermines the competitiveness of domestic firms? How policy-makers perceive opportunities and challenges for competitiveness can influence how they structure industrial policies – including trade protectionism.

It is important to recognise that green industrial policy is not formulated within a purely technocratic process. The use of public investment and policy to support green technologies means that it is subject to domestic political and social contestation. It also recognises that the nature and level of contestation varies in different economies, depending on domestic political economy dynamics. For example, in 2009 the US Senate failed to pass the American Clean Energy and Security Act that would have created comprehensive industrial policies for addressing climate change and renewables. This was because of political economy contestation of climate change legislation included in the bill (Hoffman, 2011). In contrast, China's expansion of the 12th five-year plan to include both innovation and demand policies for low-carbon technologies was a result of finding new industrial growth opportunities, a need for diverse sources of energy demand, and lowering environmental pollution (Hong et al., 2013; Thomson, 2014).

Techno-national debates centre on the loss of competitiveness in green technologies and global competitive dynamics preventing the domestic economy from realising green growth, despite investing in green industrial policy. However this chapter argues that the current literature assessing competitiveness tends to use the wrong indicators. First, these indicators are not reflective of the value added to the national economy. Indicators that use firm's market share as an indicator of competitiveness assume that all of the firm's activities occur within the domestic economy, whereas firms are a key enabler of global production networks by outsourcing or offshoring manufacturing activities (Henderson et al., 2002).

Additionally, the economies' share of either innovation or production capacity is only reflective of one kind of industrial activity that can provide value-added to the economy. Nor does the existing literature consider how the levels of value-added from these industrial activities can change with increasing global competition. The problem with current research on innovation is that it uses R&D expenditures or patents to measure innovation. These indicators are useful for learning who is dedicating efforts in which sectors and how successful they are in early-stage innovation. However innovation is not a guarantee of achieving commercialisation – especially given the difficulties in 'crossing the valley of death'. And comparing countries' manufacturing capacities provides no indication of their ability to compete to develop the next generation of technologies.

This last point is raised in the literature on emerging economies, such as China's shift away from technology transfer processes towards indigenous innovation in solar PV and wind technologies (Wang, Qin and Lewis, 2012; Ru et al., 2012; Fu & Zhang, 2011; Liu et al., 2011). These studies demonstrate that indigenous innovation has led to China's increased technological capabilities in developing more sophisticated renewable energy technologies. Nevertheless, these studies also acknowledge that Chinese actors have yet to reach a point where they compete with 'early' economies in advancing the technological frontier (Gosens & Lu, 2013; Qiu, Ortolano & Wang, 2013; Wang, 2013; Wang, Qin & Lewis, 2012; Zhang, Andrews-Speed & Zhao, 2013; Zhao et al., 2012). Fankhauser et al. (2012) also demonstrate that China has relatively low rates of green innovation in comparison with other OECD countries. Watson et al. (2014) highlight that despite targeted R&D and market-incentive programs for hybrid electric vehicles and electric vehicles, these policies have yet to demonstrate an improvement in Chinese technological capabilities to commercialise these technologies.

Collectively, this literature acknowledges that industrial activities locate in economies where comparative advantage in innovation and manufacturing exists (Altenburg, 2008; Dutz & Sharma, 2012). The green growth literature by the OECD and the Green Growth Knowledge Platform (GGKP) tries to assuage techno-national concerns by showing how different economies can realise green growth based on their comparative advantage (OECD, 2011a; Schmalensee, 2012). This chapter advances this assertion, by demonstrating how the level of value-added differs across industrial activities and changes over time. In appreciating these variations and their implications for green growth, this chapter argues for the concept of resilience as a key consideration of green industrial policy.

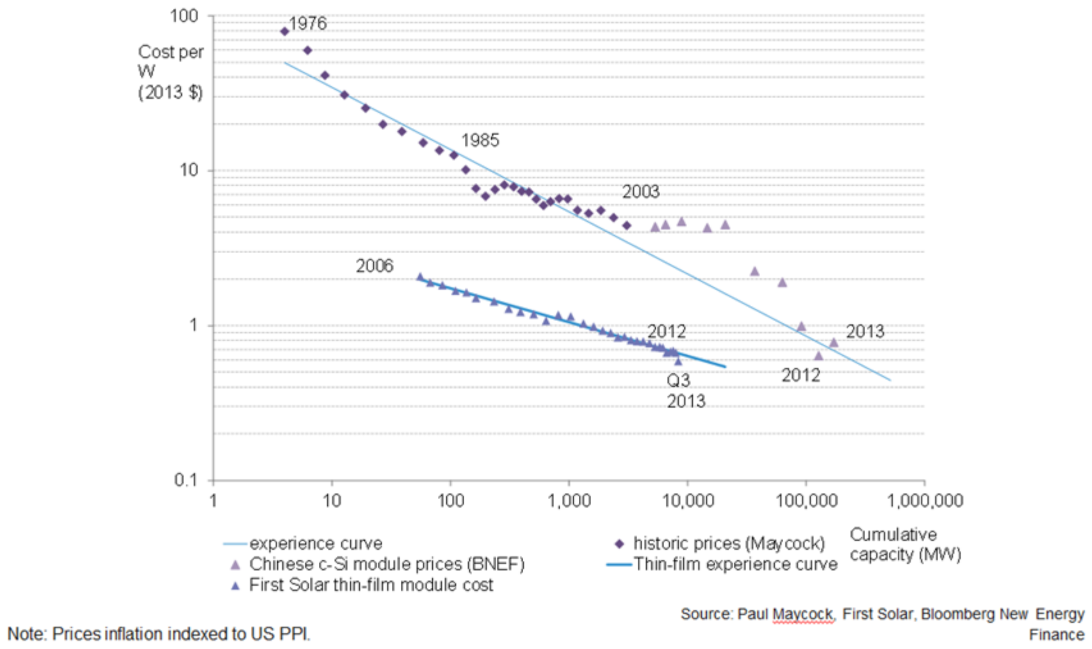
2.2 Resilience: providing long-term green growth

Evolutionary economic geography (EEG) provides a useful framework for studying the spatialisation of industries and its implications for local economic development through spatial product life cycles (PLCs) (Boschma & Frenken, 2006; Potter & Watts, 2010). In the first stage of the PLC, few economies have the innovation capabilities to compete with each other in developing viable product innovations (Maskell & Malmberg, 1999). Once a certain product innovation achieves a 'dominant design' (i.e. the greatest market acceptability), the basis for competition shifts to low-cost production (Vernon, 1966). In order to increase the scale and efficiencies of production, knowledge underlying these processes is codified into written manuals, routines or even production technologies. This codification also enables firms to transfer manufacturing to low-cost economies. Alternatively, low-cost economies can acquire these codified forms of knowledge (e.g. technological licenses, patents, production equipment) to enter these industries through manufacturing. The spatial PLC demonstrates how industrial dynamics connect economies with different comparative advantage in innovation and manufacturing (Pietrobelli & Rabellotti, 2011).

The spatial 'decoupling' of industrial activities does not conform to domestic political economy expectations of local economic spillovers between innovation and manufacturing. The political justification for investing in domestic innovation is that it will provide new technologies to expand the scope of the domestic industrial base, or that it will increase the productivity – and hence global competitiveness – of the domestic industrial base. Therefore the spatial shift of manufacturing to low-cost economies appears to undermine the expectation that innovation will provide new technological opportunities for domestic industry. Instead, it appears to suggest that in the long run, economic spillovers from domestic R&D will ultimately benefit technological opportunities for foreign economies.

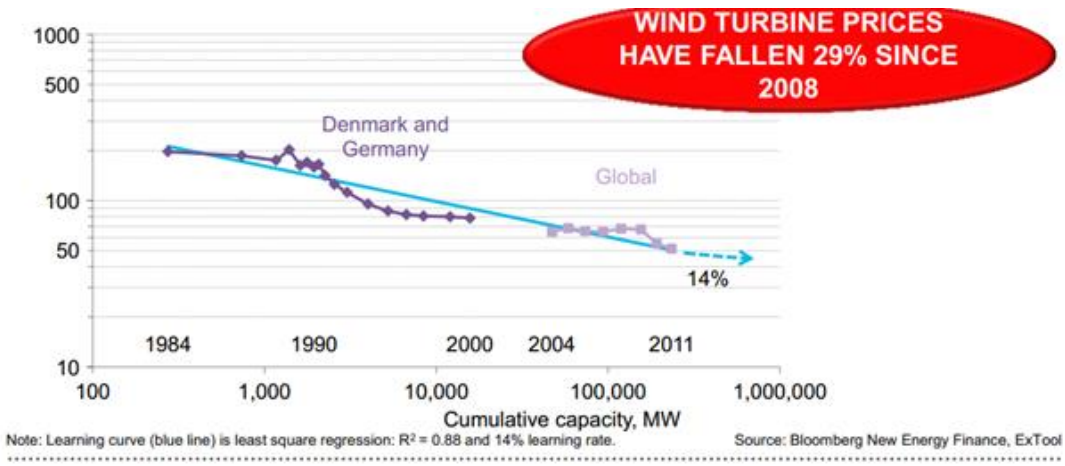
This chapter argues against this inference by focusing on how the levels of value-added to economies differ according to the stage of a technology's development. While the shift of manufacturing to low-cost economies does demonstrate a shift in absolute economic value from manufacturing, the margins of economic value derived from selling these technologies are much lower due to the expansion of global supply at this stage of industry development. Chase (2013) and Zhang et al. (2013) demonstrate that China's increase in production of solar PV has led to lower profits margins, even for Chinese producers. A number of green technologies have demonstrated these dramatic reductions in global prices over a short period of time (see Figures 2, 3, and 4 below). The most dramatic were global solar PV prices, which reduced by 80% between 2008 and 2012 due to the expansion of supply from China (Liebreich, 2013, p. 37). It should be noted that for each diagram, the light blue line indicates the experience curve for each technology, demonstrating how much costs per watt (or in the case of wind, watt hour) reduced with the doubling of manufacturing capacity – demonstrating cost reductions from improvements in efficiency and increased supply.

Figure 2. Solar PV module price reductions, 1976-2012 (USD/Watt)



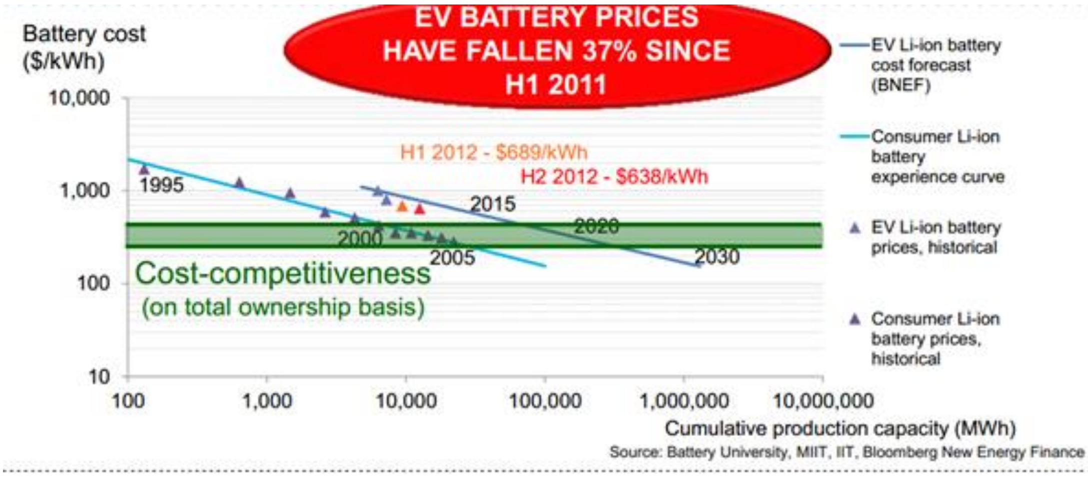
Source: Chase, 2014

Figure 3. Average levelised cost of onshore wind, 1984-2012 (Euro/Megawatt Hour)



Source: Liebreich (2013, p. 38)

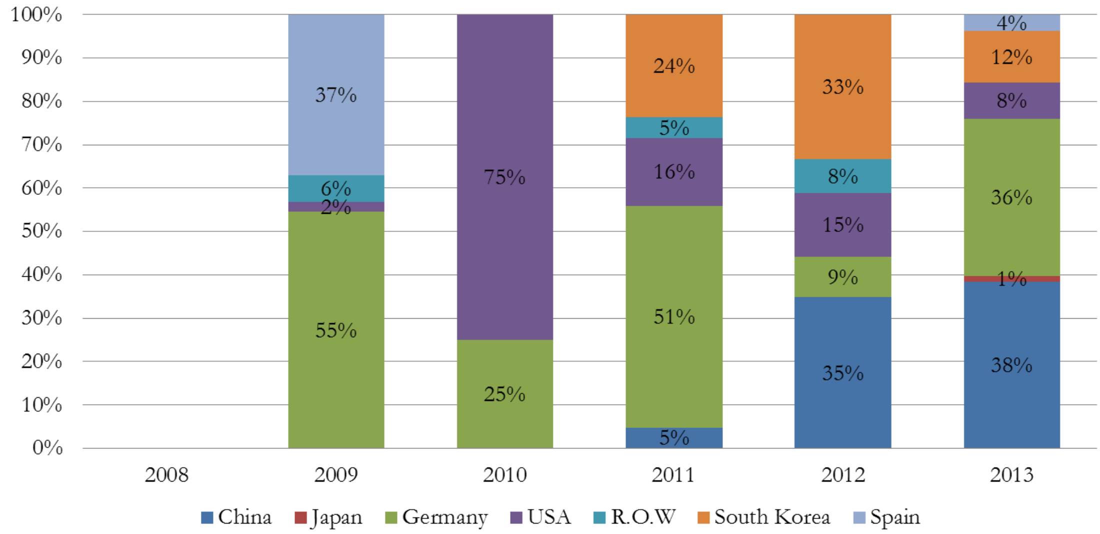
Figure 4. Lithium-ion battery experience curve



Source: Liebreich (2013, p. 39)

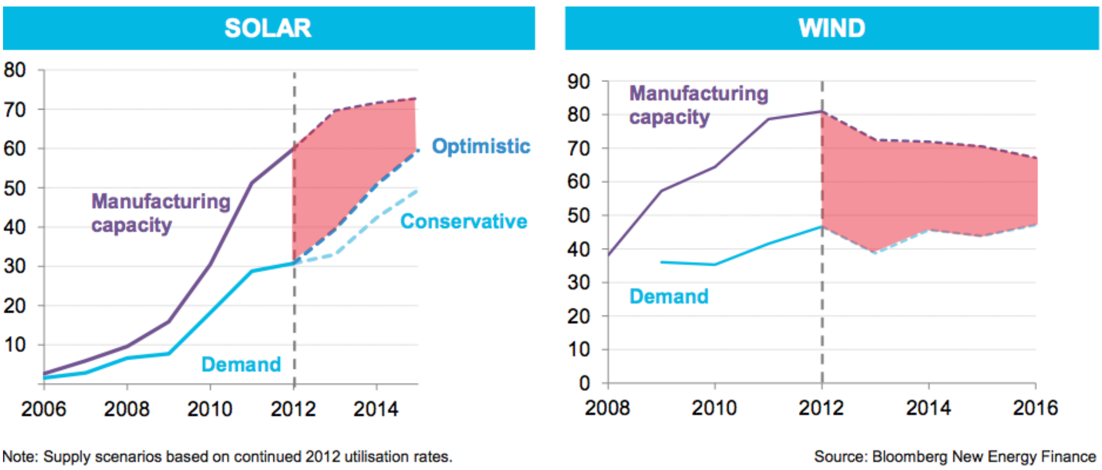
The diminished margins from manufacturing demonstrate how these economies are exposed to global competition. This exposure occurs as codification enables knowledge transfer processes that permit other economies to replicate these technologies. EEG explains that this kind of manufacturing becomes less 'territorialised' or 'localised' as it does not depend on the assets within the economy (Malmberg & Maskell, 2002; Maskell & Malmberg, 1999; Storper, 1997). However, global competition for these technologies increases as more economies gain access to codified production technologies (Audretsch & Feldman, 1996). If global markets are unable to absorb this supply, the result is a decrease in global prices and distressed margins within the producer economies. A good example of this cycle is the shutdown of crystalline PV plants that occurred first in the USA and Europe, and then even in China (see Figure 5 below). So even manufacturing-dependent emerging economies are exposed to fluctuations in global supply and demand (see Figure 6 and 7 below).

Figure 5. Decommissioned PV cell manufacturing capacity by country and rest of the world (R.O.W.), %



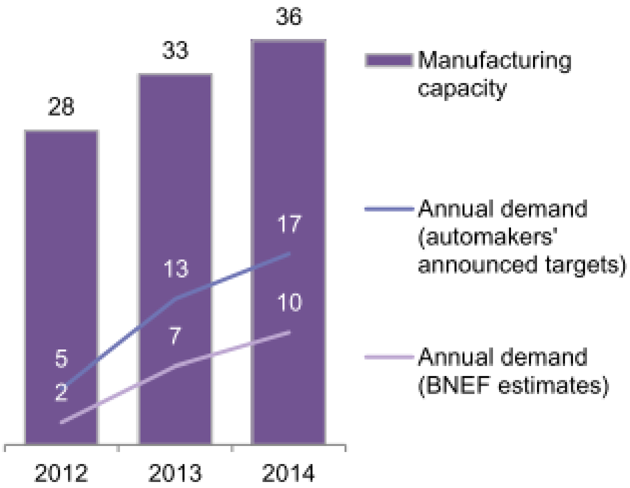
Source: Calculated from BNEF database

Figure 6. Global supply and demand of equipment (GW), 2006-2015



Source: Liebreich (2013, p. 6)

Figure 7. Global supply and demand for lithium-ion batteries for electric vehicles



Source: BNEF (2013, p. 13)

In demonstrating the diminishing returns to economic value from manufacturing, this chapter reasserts the importance of innovation in making economies resilient to global competition. An economy's resilience is determined by its ability to either: 1) retain these activities within the local economy, even as other regions compete to participate in these same industrial activities; or (2) adapt to the shift of an industrial activity by creating new activities that yield economic value (Hassink, 2010; Maskell & Malmberg, 1999; Storper, 1997). The spatial nature of innovation enables economies that are successful in innovation to achieve both scenarios.

Unlike manufacturing, innovation tends to be more spatially embedded (or 'territorialised') in local economies (Maskell & Malmberg, 1999; Storper, 1997). EEG demonstrates that innovation activities are actually clustered at the local level because they rely largely on tacit exchanges of knowledge amongst actors, best facilitated through face-to-face interactions (Storper & Venables, 2004). Furthermore, cultural institutions – such as language and customs – shape the nature of these interactions and the development of their networks (Boschma, 2005). Therefore the development of national innovation systems makes them unique to the local economy. Saxenian's (1996) comparison of Boston with Silicon Valley examines how innovative clusters within the same country have developed very different innovation systems. The primary factors are due to the types of actors (and their networks) and the path-dependency of innovation experience, which has resulted in very different cultural approaches to risk. The territorialisation of innovation demonstrates how countries that have developed strong national systems of innovation can retain innovation, despite losing manufacturing (Boschma & Kloosterman, 2005; Gertler & Levitte, 2005).

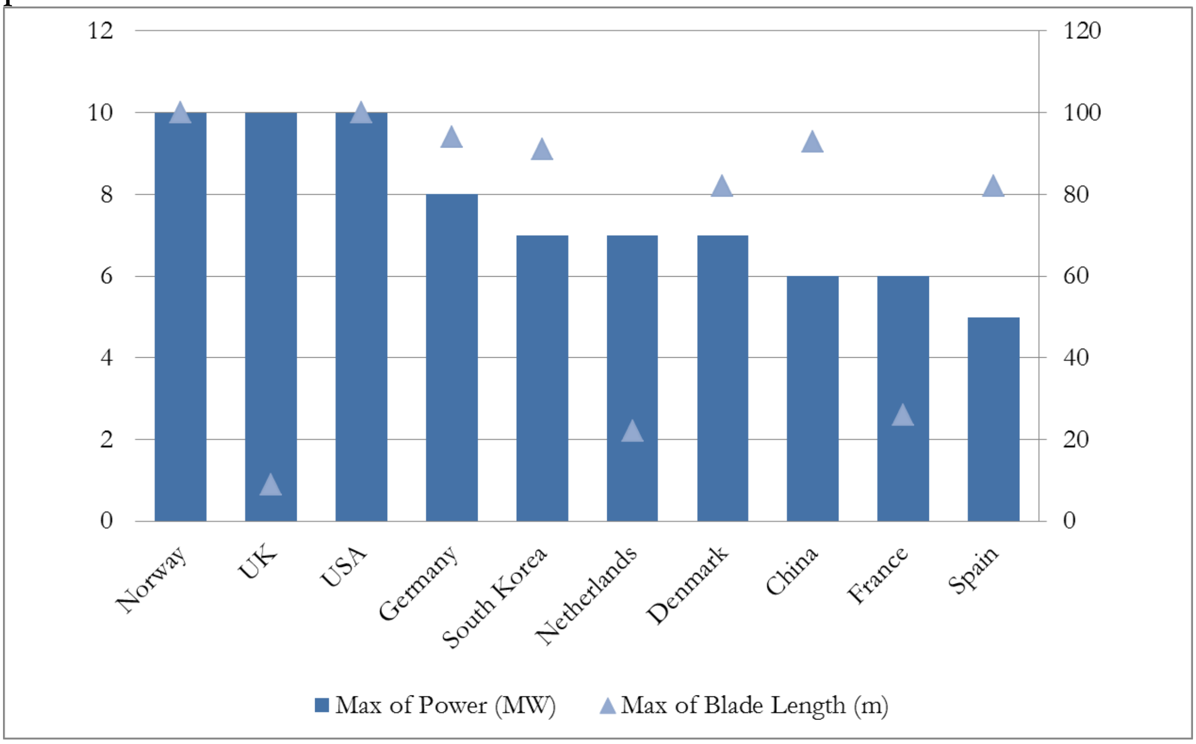
The territorialisation of innovation also means that an innovation system cannot be replicated by a foreign economy (Storper, 1997). The implication is that countries that undertook catch-up strategies through manufacturing still need to develop their national innovation system. As Section 2 demonstrates, though emerging economies have reduced their reliance on foreign economies for technology, they still invest in these economies to access knowledge spillovers (Ernst, 2009). For example, Lewis & Wiser (2007) demonstrate that India's Suzlon opened their international headquarters in Aarhus, Denmark to benefit from leading innovation research there. This example indicates how the territorialisation of innovation attracts investment from foreign economies, rather than losing out to them.

The importance of retaining innovation is that it enables economies to manufacture technologies that have high value. Manufacturing for these technologies takes place in leading innovation hubs due to the need for highly-skilled workers who gain their expertise from these very same hubs (Maskell & Malmberg, 1999; Moretti, 2012). These technologies have high value because other economies cannot reproduce them. A Pew (2013) study shows that bilateral trade flows between the US and China in solar PV, wind and energy smart technologies had the net export value of USD 1.6 billion for the USA in 2011. The study demonstrates that the comparatively low value of Chinese exports to the USA was due to the global supply glut and consequently low market prices of final products. In comparison, the USA exported production equipment, highly specialised materials and sub-components that help Chinese manufacturers increase their production capacity, which Chinese firms have not yet learned to develop.

In cases where other economies learn to produce these technologies, early-innovators can adapt by developing more sophisticated designs or next generation technologies. By developing and retaining strong innovation systems, these economies can capitalise on their knowledge to optimally advance the frontier (see Figure 8 as an example for wind technologies). For example, the next generation of solar technologies includes thin-film technologies. The only firm that has successfully commercialised this is the American company First Solar. As shown in Figure 2, it can produce thin-film technologies at a lower cost than the dominant crystalline PV technologies. Innovation studies of green technologies demonstrate there is considerable scope for growth through innovation by means of knowledge complementarities. Noailly & Shestalova's (2013) comparison of inter-technological spillovers suggests that solar PV and energy storage technology can have applications outside their own fields. Therefore innovation increases the adaptability – and hence resilience – of economies as manufacturing shifts.

Therefore this chapter argues that economies that have successfully innovated green technologies continue to have opportunities to realise green growth. However these economies need to continue to invest in R&D in order to capitalise on their accumulation of knowledge capital. Fankhauser et al. (2013)demonstrate that countries like Japan and Germany have a high potential to convert their innovative capacities to producing green technologies in the automobile, materials and specialised production equipment. However countries such as the UK, which has comparative advantage in chemicals, pulp and paper, batteries, and cement industries, have low green innovation levels for green technologies. By not capitalising on their comparative advantage to undertake green innovation in these sectors, the UK can miss out on opportunities to realise green growth in the long run.

Figure 8. Top ten countries in developing wind turbines according to maximum power and blade size



Source: Derived from BNEF database

2.3 Spatial characteristics of industrial activities and implications on value-added to the local economy

This section expands on EEG's study by focusing on the spatial characteristics of different technologies affects the spatialisation of industrial activities. These differences in technologies' characteristics can affect where innovation, manufacturing and markets locate in relation to each other. The spatial distance between these activities can thus determine the ability for economies to realise economic-value within the geographical confines of the economy. Appreciating these differences in spatial characteristics can provide a more nuanced approach to structuring industrial policy for various technologies that maximises 'green growth' to the domestic economy.

2.3.1 Industrial activities that have low spatial mobility will require manufacturing to be spatially proximate to markets

The level of spatial mobility of technologies affects the distance between industrial activities. High spatial mobility means that technologies (and their sub-components) have low trade costs, so can be produced in disparate places and delivered to final markets. However, industrial activities that have low spatial mobility need to be spatially concentrated as the high costs of trade undermine any advantage there may otherwise be to obtaining technologies from lower cost economies. Therefore industrial activities with low spatial mobility can monopolise the entire industrial complex within the domestic economy, producing economic spillovers throughout the industrial cluster.

The difference in these spatial characteristics can help explain why certain technologies are more spatially dispersed than others. Wind technologies (and their sub-components) are physically large, thereby having high shipping costs (Pew, 2013). Shipping also increases the risk of damage to components, potentially leading to malfunctions. In response to these conditions, manufacturing plants for wind components tend to be close to markets (Gosens & Lu, 2013; Lewis & Wiser, 2007). Biomass electricity generation is another example of a green industry that has high transport and logistics costs, with the sourcing biomass products accounting for a significant proportion of these overall costs (WEC & BNEF, 2013). These studies show that large-scale markets for wind and biomass technologies tend to source technologies from local manufacturing plants. In contrast, solar PV technologies have low transport and logistics costs. The modularisation of solar PV enables its sub-components to be produced and assembled in discrete economies and exported to final markets. Therefore solar PV production networks are integrated globally (Wang, 2013) and vulnerable to trade tariffs (Zindler, 2012).

Institutional factors can also increase the cost of trade and affect the spatial mobility of technologies. For example, an obvious 'hard' institution is a trade regime that favours locally-produced technologies over those produced outside the country. This can be achieved through the obvious route of import tariffs, but another means is through local content rules. The latter requires that imported technologies are produced using a defined level of inputs sourced in the target economy. Industrial policies for Brazilian and Chinese[3] wind markets, as well as Chinese and Japanese solar PV markets, all have local content rule restrictions (Lewis & Wiser, 2007; Schwarzer, 2013; UNEP, 2013). Therefore techno-nationalist industrial policies can structure domestic market mechanisms to retain manufacturing within the domestic economy despite global competition.

Another institutional variation that increases the cost of trade is differences in intellectual property rights (IPR) regimes. Firms are able to sell patents and technological licenses to foreign economies, or undertake research partnerships with foreign technologies. However Dechezleprêtre et al. (2011) demonstrate how the weak enforceability of IPR regimes reduces the propensity for technology transfer. Ernst (2011) proposes international standardisation of patent laws to overcome these institutional differences. Lewis (2014) highlights the important of joint research collaborations to engender trust. All in all, institutional factors can limit the spatial mobility of otherwise highly mobile and codified forms of innovation.

2.3.2 Green industrial policy: realising green growth through supply and demand of technologies

So far this chapter has largely focused on how green industrial policy can engender green growth through the production of green technologies. It argues that techno-national debates that focus on protecting domestic producers of technologies can harm the potential economic value-added realised through market expansion. Expansion of green markets is an important premise of green growth. The transition to a low-carbon trajectory occurs through

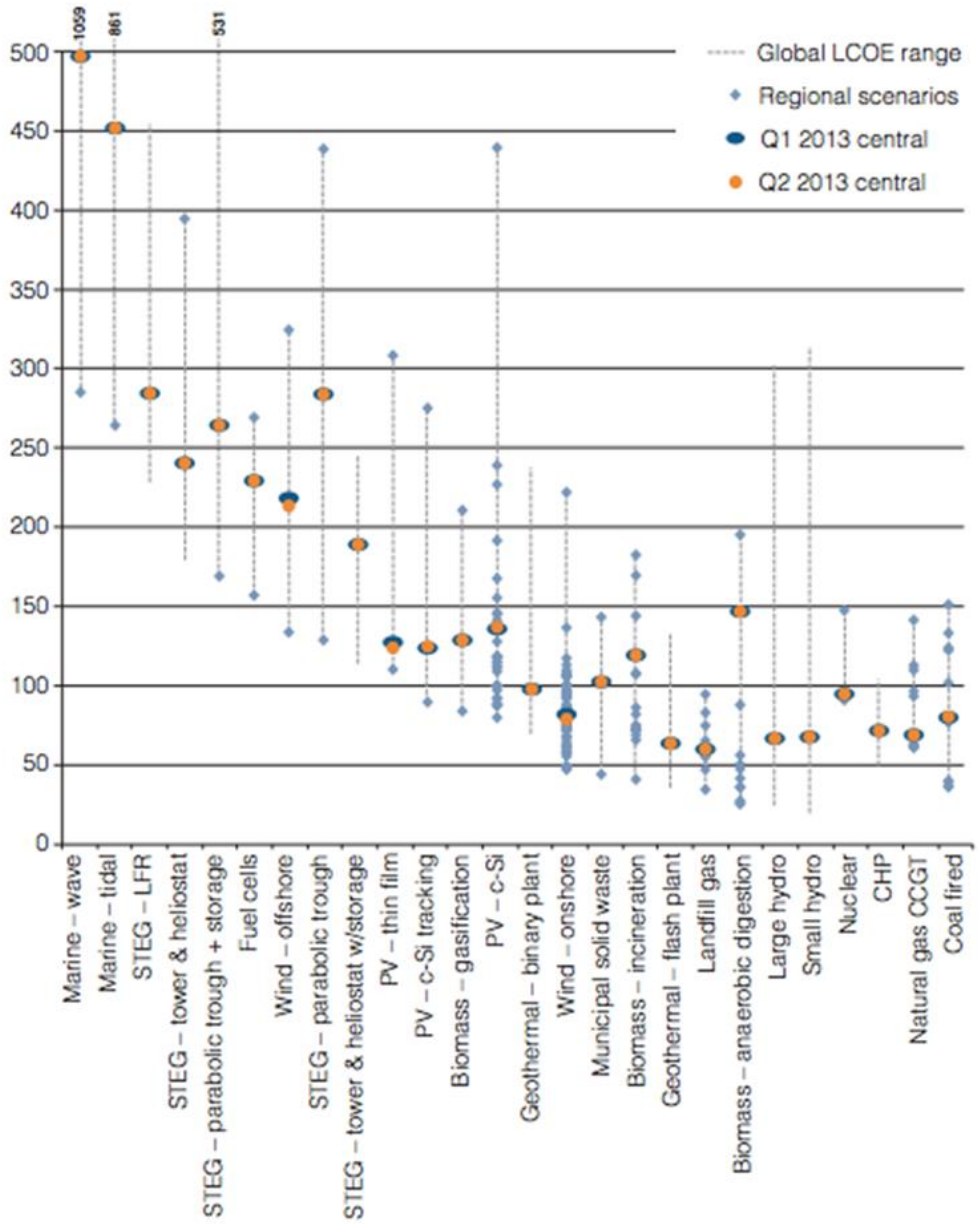
[3] In the case of Chinese wind markets, foreign firms are required to also take joint-ventures with a domestic firm in order to sell to local markets.

the supply and *diffusion* of green technologies. A joint study by WEC and BNEF (2013) demonstrates how price reductions in solar and wind technologies have brought the levelised costs of electricity into the same range[4] as fossil-fuel generation (see Figure 9 below). Furthermore, industrial policies that support green markets can also attract both domestic and foreign investments to expand these markets. BNEF estimates that global asset financing for newly installed renewable energy capacity, and deploying energy smart technologies, was USD 207 billion in 2013 (Mills, 2014, p. 3). In comparison, global investments into the supply side of technologies were only USD 45 billion (Mills, 2014, p. 3).

Lastly, the build-out of green markets creates employment opportunities in various sectors (Dicken, 2011; Muro, Rothwell, & Saha, 2011). These include marketing, finance and insurance, as well as labour related to installing, operating and maintaining technologies. A joint study by Swiss Re and BNEF calculate that insurance for renewable energy can grow to USD 1.5 – 2.8 billion based on the construction, operation and market-related risks related to the build-out of solar PV and wind markets (Turner et al., 2013). Another potential benefit is the dependence of markets on *domestic labour*, which means that these jobs are less exposed to international competition.

[4]The ranges are dependent on electricity markets and financing structures of different economies.

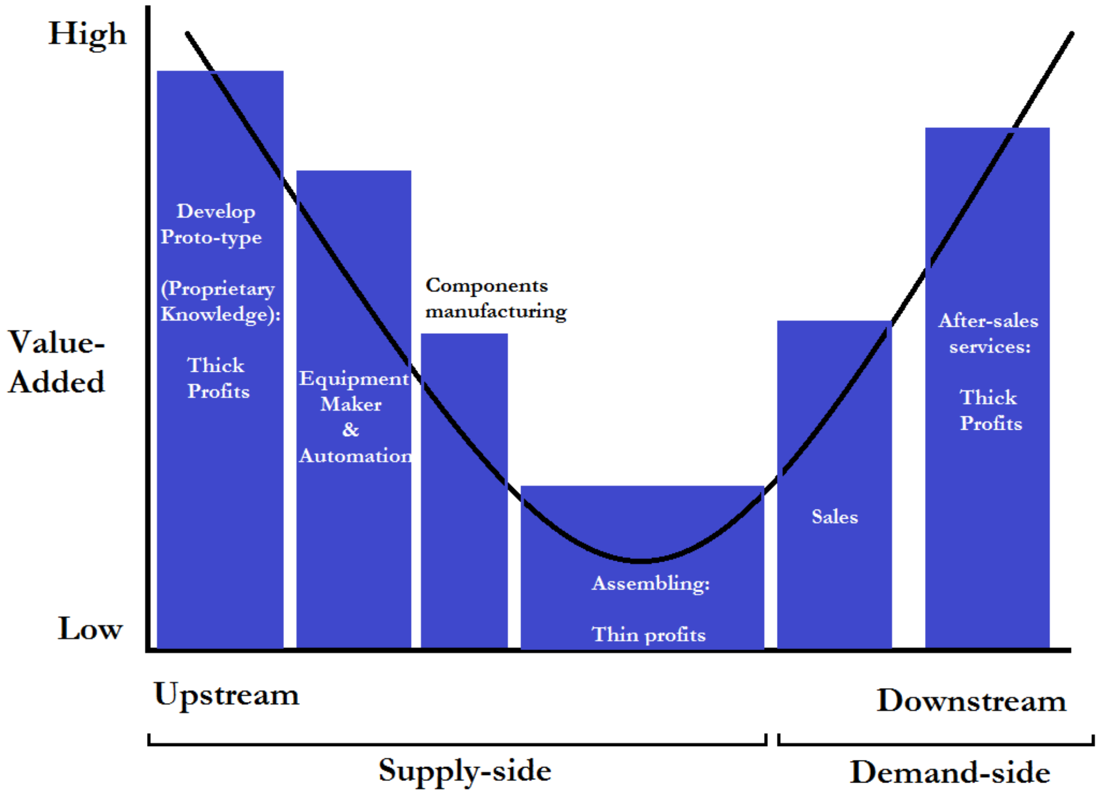
Figure 9. Levelised costs of electricity for different technologies



Source: WEC & BNEF (2013, p. 10)

Therefore economic value can be derived from levels of global supply and domestic demand of technologies. The spatial characteristics of technologies then have implications for the level of value-added to the local economy. The economic geography and business management literature recognise that manufacturing has the lowest value-added to the economy (Dicken, 2011; Porter, 2011). In comparison, innovation provides the highest value due to the lack of replicability of technologies. Market activities' dependence on domestic labour also increased value-added to the domestic economy (see Figure 10 below).

Figure 10. Value-added from different industrial activities



Developed from: Masahiko & Haruhiko (2002)

The spatialisation of certain technologies demonstrates that domestic markets are not restricted to domestic supply. Instead the source and level of technology supply is influenced by: (1) replicability of technologies (based on how many economies can make these technologies, and hence affect global supply); and (2) spatial mobility of technologies (determining whether costs of trade will increase or decrease access to foreign supply of technologies). Technologies with high spatial mobility indicate that both domestic and foreign firms have access to domestic markets. However the intensity of competition for these markets is dependent on the level of replicability. If only a few firms can produce these technologies, sellers can charge high prices to sell to domestic buyers. However if many firms can reproduce these technologies, it becomes a buyer's market. Though supply-side firms in the domestic economy will face low profit margins, the economic value to the local economy can be counteracted by market expansion from cheap technologies.

Table 3 below summarises the conceptual framework of how replicability and mobility of technologies can affect the balance of economic value to the local economy. It looks at the trade-offs in value between buyer's and seller's markets based on supply of technologies.

However, market demand needs to be high enough to absorb this supply and the importance of diffusing green technologies to achieve a low-carbon trajectory – along with green growth from market expansion – provides justification for demand-side policies. Though the prices of green technologies can decrease due to increases in global supply, it does not guarantee that green technologies will be cost-competitive to their brown incumbents. These dynamics illustrate the importance of economies' instituting demand for green technologies – regardless of whether it provides economic spillovers to domestic manufacturing. Ironically, this techno-national focus on achieving economic growth from green industrial policy can subsume the priority of becoming "green the economy" through technological diffusion. The table below demonstrates that policy-makers should *balance* priorities in supporting both the supply of and demand for technologies.

Table 3. Determining level of competition in domestic markets based on spatial characteristics of technologies

	Replicability of technologies	
Spatial mobility of technologies	**Low**	**High**
Low	**Seller's market: Low competition in domestic markets creates high value for domestic producers.** Supply-side actors can command high technology prices because other firms cannot produce these technologies. Domestic economies can potentially still benefit from having local manufacturing plants, even if the firms are headquartered abroad. The high costs of transport favours manufacturing to be located near the market [e.g. large offshore wind turbines].	**Both buyer's and seller's market: High competition in domestic markets.** High costs of trade means manufacturing will need to be close to markets. However the replicability of these technologies could mean that multiple firms compete to supply technologies to domestic markets. A more competitive domestic market can still benefit market actors [e.g. biomass markets that have multiple companies competing for domestic market share].
High	**Seller's market: Low competition for domestic and foreign markets creates high value for domestic producers.** Few supply-side actors can produce these technologies. Furthermore these technologies have high spatial mobility that allows them to be sold in multiple countries. Therefore supply-side actors can reap high levels of value in both domestic and foreign markets [e.g. First Solar's thin-film technologies].	**Buyer's market: Intense competition for domestic and foreign markets.** High technological replicability means that multiple actors from different economies can produce these technologies. The low costs of transport indicates that demand can be met by global supply. This leads to low profit margins for supply-side firms, to the benefit of markets [e.g. crystalline PV technologies].

Source: Author schema based on Boschma (2014); Dicken (2011); Storper (1997)

2.4 Conclusion

This chapter has sought to reveal how the spatial dynamics of technologies and industrial activities affect domestic green growth opportunities. It recognises that the political economy goal of green industrial policy is to maximise economic returns to the local economy. However it argues that techno-nationalist perspectives can misconstrue where green growth opportunities actually exist. Maximising economic value within the economy does not always occur through spillovers between domestic innovation and manufacturing – especially as these technologies become subject to cost competition globally.

EEG uses the concept of resilience to investigate whether the local economy can withstand global competition. It argues that the ability of domestic industry to appropriate returns is not through highly replicable manufacturing technologies, which only expose them to global competition and commodity price fluctuations. Instead, the concept of resilience shows how success in innovation enables these economies to concentrate on manufacturing high-value technologies those other economies cannot reproduce. Furthermore, economies can capitalise on their knowledge accumulated through innovation to develop the next generation of technologies.

This chapter also considers how the spatial characteristics of technologies can affect whether green growth opportunities are realised through the supply or demand of local economies and argues that green industrial policy should consider how the spatial characteristics of technologies affect supply and demand dynamics. These dynamics can affect how much economic value can be added either through domestic supply and the build-out of markets. Policy-makers should also reconsider whether trade policies that protect domestic markets from foreign competition can have larger opportunity costs for green growth through market expansion, particularly in cases where technologies are highly replicable and have high spatial mobility.

Having said this, techno-national policies to protect domestic industry can be justified under two circumstances. The first is ensuring that the IPR of domestic innovative actors is protected so as to reward (and encourage) investments in innovation. Auerswald (2012) and Harvey (2008) studies demonstrate that weak IPR regimes that do not protect against knowledge spillovers dampen the willingness of innovative actors to invest in risky innovation. Therefore the development and *enforcement* of international standards for IPR are incredibly important. The second case is when developing countries use localisation policies to help the fledgling domestic industry develop technological capabilities (Lewis & Wiser, 2007).

Both circumstances have their own controversies. Protection of IPR can hamper the diffusion of green technologies that are essential for developing countries' mitigation and adaptation efforts (Dechezleprêtre et al., 2011; Lewis, 2014). Ockwell et al. (2010) argues that developed country concerns for green IPR protection can be overstated as developing countries are not necessarily 'supply competitors'; although firms in developing countries can get access to technologies to build their technological capacity, they have not been able to access cutting edge IPR. However, green IPR diffusion is needed to help developing countries build their capacity to engage with low-carbon development. In terms of fledgling industry protection, D'Costa (2012) highlights how persistent market protection for the Indian industry created a monopoly situation prior to trade liberalisation in the 1990s, with disincentives for domestic firms to increase their technological capabilities to become globally competitive. In this case, protection of domestic markets for the domestic industry creates high costs for both domestic development (in terms of improving technological capabilities) and domestic consumers (in terms of accessing high quality foreign goods).

Further research questions can be developed using EEG's study of the spatialisation of technologies and its implications on local economic development. The spatial production life cycle shows that in the first cycle, there is spatial decoupling between innovation and manufacturing activities. Questions still remain, however. Does this spatial distance between innovation and manufacturing persist over different successive cycles of technologies? Or do emerging economies capitalise on the close spatial relationship between indigenous innovation and manufacturing to develop alternative technologies? Even if innovation and manufacturing occurs in countries where comparative advantage exists, does it mean an increase in research collaborations between these countries? The motivation would be to enable learning geared towards process innovations or the commercialisation of early prototypes. Or do countries collaborate with others that have similar technological capabilities? Lastly, do domestic political economy developments in green technologies affect how research institutes interact with counterparts in competitor countries? These questions have the potential to shed light on the resilience of economies pursuing green growth from supply-side activities.

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Chapter 3: First-mover advantage and the spatial evolution of innovation and manufacturing in the solar PV industry

Considering the spatial relationship of innovation and manufacturing over time

ABSTRACT. Within the context of debates about the resilience of "first-mover advantage" (FMA) in clean tech, this chapter explores the changing spatial distribution of economic activity in the global solar photovoltaic (PV) industry. Conceptually, we situate our analysis in the product life-cycle model, which gives rise to two hypotheses. The spatial decoupling hypothesis posits that there will be a spatial separation between innovation and manufacturing over time, with first-movers retaining competitive advantages in innovation; while the spatial recoupling hypothesis suggests that innovation will eventually follow manufacturing as it migrates to late-comers. While there has been a major shift of manufacturing capacity to late-comers (notably China), we find only partial evidence of recoupling, at least when we measure innovation by patents or countries' production of best-in-class solar cells. Using scientific research publications provides a slightly different picture, suggesting that late-comers are increasingly catching up with first-movers. We conclude by discussing the relevance of our findings for debates about the importance of proximity for innovation and policy-inducted FMA.

3.1 Introduction

According to theories of first-mover advantage (FMA), firms which gain an early lead in a particular industry may go on to enjoy long-term competitive advantages (Kerin et al., 1992). Within the context of the so-called "clean tech" industry (Caprotti, 2011; Cooke, 2008), ideas of FMA have been drawn upon to argue for an important role for early state intervention to support the development of "green" national champions. One influential variant of this thesis, famously espoused by Porter (Porter, 1991; Porter & van der Linde, 1995) places strong emphasis on properly designed public environmental regulation to stimulate the early innovation of environmentally sound technologies. Others have highlighted the importance of deploying a wider set of industrial policies (Wallace, 1996). Either way, the underlying assumption is that the early adoption of state-based demand- and supply-side measures may be instrumental in generating first-mover advantage in this emerging field of technology. Moreover, by implication, those countries "late to the game" in the development of clean tech might subsequently struggle to "catch-up".

Couched in the policy-oriented discourse of ecological modernisation and, latterly, green growth, such ideas have proved influential. Indeed, historical experience has lent weight to the predictions of policy-induced FMA, with early state interventions in countries such as Germany, Denmark and the US apparently supporting the development of domestic environmental technology industries from the 1960s onwards (Beise & Rennings, 2005; Huber, 2008; Jacobsson and Lauber, 2006; Popp, 2006). However, the past decade has witnessed the dramatic growth of a clean tech industry in a number of emerging economies, despite being comparative late-comers (de la Tour et al., 2011; Lema & Lema, 2012; Liu & Goldstein, 2013). For policy-makers, such trends have fuelled fears of a wholesale shift of the emerging clean tech industry from West to East, and called into question the public support provided to the domestic clean tech industry in developed economies (Pegels & Lütkenhorst, 2014). Moreover, of direct concern in the present chapter, the recent growth of the clean tech industry in emerging economies would appear to challenge the idea that countries can retain their FMA in emerging sectors.

For economic geographers, the geographic spread of the clean tech industry is unlikely to come as a surprise. Industrial and product life-cycle theories have long posited a spatial shift of manufacturing activity from "core" (i.e. developed, first-movers) to "peripheral" (i.e. developing, late-comer) countries as industries mature (Vernon, 1966). More recently, research into production networks and chains has drawn attention to how a growing number of industries are increasingly organised on a transnational basis, with different functions and operations involved in the production, distribution and consumption of goods and services located in different countries/regions (Coe et al., 2004; Dicken, 2010). An important insight from this literature is that, from the perspective of regional and/or national economic prosperity, what matters is the control of high-value added activities. This, in turn, points to the importance of retaining competitive advantages in innovation. Innovative capabilities and outputs can be interpreted as intangible assets (Mudambi, 2008). Such assets are more difficult to replicate, rendering them the source of value-added and prosperity for longer periods of time (Poletti et al., 2011).

This chapter intervenes in these debates by exploring spatial shifts in the innovation and manufacture of solar photovoltaic (PV) technology over time. A central aim is to examine whether countries which first became dominant in innovation and manufacturing retain their innovative advantages as manufacturing shifts to emerging economies. Put differently, does innovative activity follow dominance in manufacturing over time, or does it remain with first-movers? To answer these questions, we map the evolving geography of the solar PV industry, charting the spatial distribution of (a) manufacturing and (b) innovation over the period 1976-2012.

Our research makes two important contributions. First, we contribute to debates in economic geography about the dynamic spatial relationship between innovation and manufacturing over time (Boschma, 2005; Morgan, 2004). These debates centre on whether learning from spatially proximate manufacturing activities is necessary for enhancing the capability of innovating actors to improve the technological performance of successive products and advanced manufacturing technologies (Aoyama et al., 2011; Mudambi, 2008). They also centre on the "resilience" of economies (Hassink, 2010; Martin & Sunley, 2006) and the degree to which accumulated, territorially-embedded innovation capabilities enable first-movers to adapt to new competitive realities. On the one hand, it could be that innovation and manufacturing spatially separate as the industry matures, with the factors which provide competitive advantage in manufacturing in late-comers failing to translate into innovative capabilities. Alternatively, whilst spatial decoupling may take place in the short-term, it could be that innovative activity eventually follows manufacturing. In particular, technological learning gained through manufacturing and the absorption of foreign technology may give rise to indigenous innovation capabilities required to successfully participate in the next round of innovation (Ru et al., 2012; Yeung, 2007). We refer to this dynamic as spatial recoupling.

Second, by investigating the reality of spatial decoupling and recoupling in the context of solar PV, we seek to address an important gap in current understanding regarding the economic sustainability of FMA. The growth of clean tech in several emerging economies raises questions about the advantages of being a first-mover; the degree to which late-comers (or "followers") can free-ride off first-mover technological investments (Lieberman &

Montgomery, 1988; Pegels & Lütkenhorst, 2014); and whether first-movers become "locked-into" technological trajectories which make it difficult for them to adjust to external shocks from new sources of competition (Martin & Sunley, 2006). A number of chapters offer empirical support for the idea that a combination of demand- and supply-side factors was instrumental in the early dominance of a handful of developed countries in the clean tech sector (Brandt & Svendsen, 2006; Jacobsson & Lauber, 2006). More recently, several case-studies have documented the rise of the clean tech sector in emerging economies (de la Tour et al., 2011; Dutz & Sharma, 2012; Hansen & Ockwell, 2014; Lewis, 2007; MacLaughlin & Scott, 2010; Mathews et al., 2011; Pueyo et al., 2011). However, missing from the literature have been more systematic, comparative analyses which have sought to go beyond the analysis of either first-movers or late-comers to examine the changing distribution of economic activity in clean tech across countries from both of these categories.

A particular novelty of our study is that it uses multiple measures of innovative activity. Previous larger N, comparative research which has examined innovative capabilities and outputs in clean tech has tended to rely exclusively on patent counts. For sure, these counts are not without their merits. Yet they can also be misleading. Most importantly, patents counts alone say nothing about the "quality" of innovations, and the identity of countries at the frontier of inventive activity (Dechezleprêtre et al., 2011). Precisely for this reason, as well as academic research publications, we use a novel measure of "best-in-class" product innovations.

The rest of the chapter is organised as follows. Section 2 outlines the product life-cycle (PLC) model and elaborates on two competing hypotheses (spatial decoupling and recoupling) regarding the dynamic relationship between manufacturing and innovation. The research design is presented in Section 4, followed by results in Section 5. In brief, while there has been a major shift of manufacturing capacity to late-comers (notably China), we find only partial evidence of recoupling, at least when we measure innovation by patents or countries' production of best-in-class solar cells. Section 6 provides discussion and conclusions.

3.1.1 Spatial decoupling and recoupling

3.1.2 The product life cycle

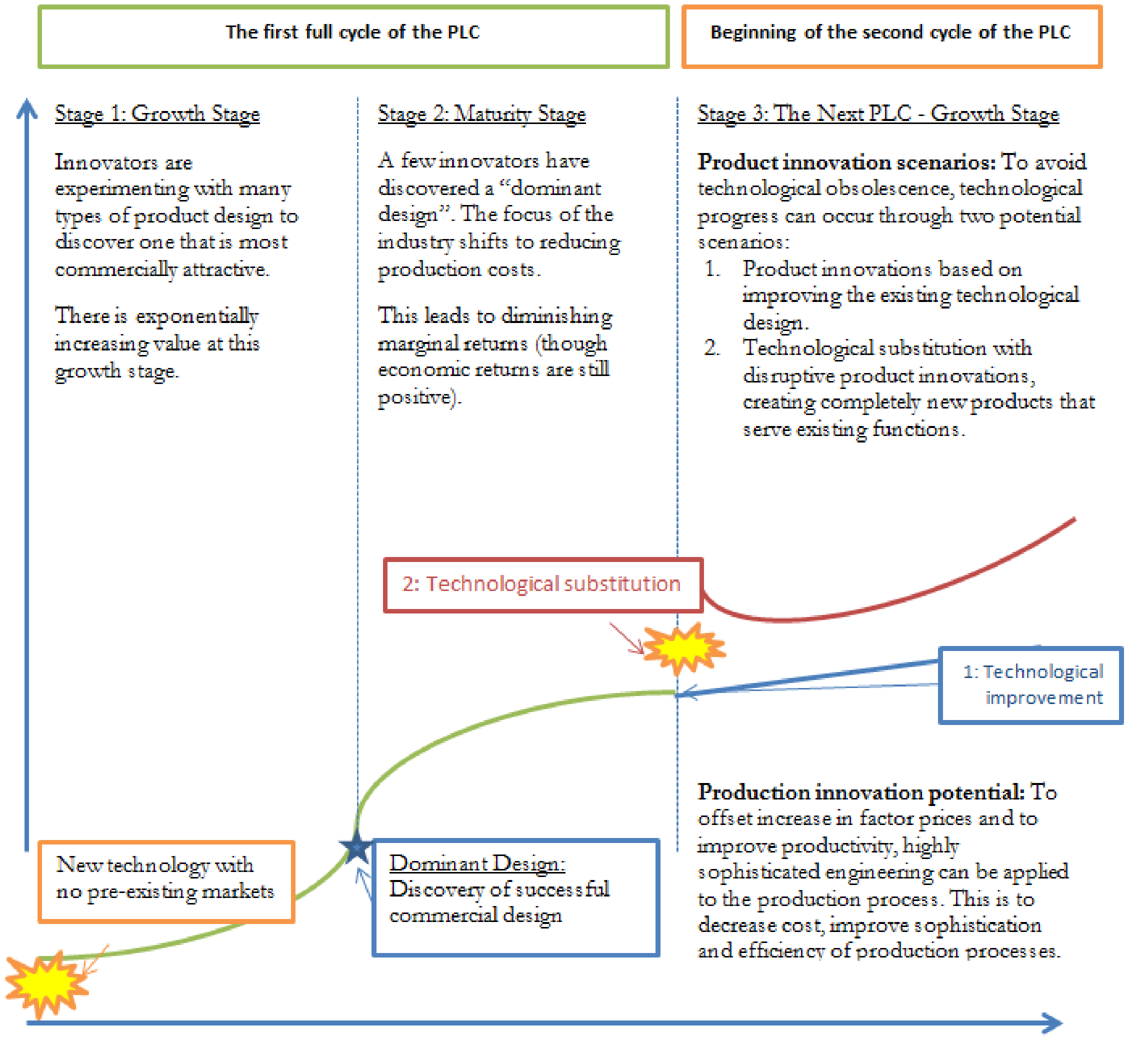
Our conceptual starting point in the present chapter is the product life-cycle (PLC) model which provides a framework for beginning to understand the spatial relationship between innovation and manufacturing in solar PV. The PLC posits that technologies go through essentially two main stages (Klepper, 1996). In the initial growth stage, innovative efforts lead to the development of new technologies. The basis of competition between innovators and entrepreneurs is product innovation. These actors seek to make their experimental designs technologically and commercially attractive by "learning-by-searching" which, to a greater or lesser extent, involves trial-and-error (Callander, 2011). At this stage, access to strategic niche markets (SNM) often assumes an important role, in that they provide an environment in which to incubate new technologies and create learning feedback loops for the product's further development and performance improvements of associated process technologies (Kemp et al., 1998).

Yet once a technology achieves a "dominant design" – where a certain technological design gains the greatest market acceptability – the technology matures. At this stage, the basis of competition shifts from product innovation towards reducing production costs, and expanding market share though process innovations (Abernathy & Townsend, 1975). The knowledge that underpins production of technologies becomes codified into hardware technologies, production routines and written manuals (Tidd & Bessant, 2009). Codification of production technologies enables knowledge underpinning production to be transferred across geographic space from first-mover economies, where technology was originally developed, to economies that have the comparative advantage in high-volume manufacturing (Mudambi, 2008; Potter & Watts, 2010). Technologies may be transferred through foreign direct investment (FDI) as multinationals invest in production facilities in late-comer economies with lower manufacturing costs (Dunning & Lundan, 2008). Alternatively, domestic firms in economies can acquire this codified knowledge to manufacture technologies in the local economy, including through imports of embodied technology, licencing and original equipment manufacture (OEM) (Hobday, 1995). In either case, later-comer economies are assumed to be able to capitalize on their comparative advantage in manufacturing to enter these new technological industries, sometimes as part of outsourcing strategies by firms in first-movers (Xiaobo et al., 2010; Yeung, 2007).

The growth and maturity stage constitutes one cycle of the PLC. The next iteration of the PLC begins with certain declines at the maturity stage (Klepper & Simons, 2005). The main risk at the maturity stage is of technological obsolescence, where the global markets are saturated with the current dominant design, or existing technologies are no longer cost or performance competitive. Thus a new cycle of competition occurs – with the potential of at least two different technological trajectories. In one instance, existing users upgrade to newer versions of the dominant design (e.g. upgrading from an iPhone 5 to an iPhone 5C). An important part of the innovation that goes into improving the existing dominant design is the upgrading of production equipment used in factories to manufacture products. These kinds of process innovations are considered to be of a high-level because they require advanced engineering in production equipment design and, increasingly, automation (Hansen & Ockwell, 2014). Therefore, at this stage, innovation may be focused around high-level process innovation as well as product innovation. The second potential scenario is when a completely new kind of product acts as a complete substitute for the dominant design (e.g. technological substitution occurs from the telegraph, to the telephone handset, to the mobile phone) (Winter, 1984). Again, this is likely to require significant process innovation, and the production of a new generation of manufacturing technologies.

A central focus in the present research is on the second and third stage of the PLC. For many categories of clean tech, the initial growth phase took place in developed economies, often supported by domestic governments (Brandt & Svendsen, 2006; Huber, 2008). Yet less well understood is the degree to which the shift of manufacturing to late-comers is accompanied by a shift in the locus of innovative activity to these economies. We explore this question, examining two competing hypotheses outlined below, the spatial decoupling and the spatial recoupling hypotheses (Figure 1).

Figure 1. The conceptual relationship between manufacturing and innovation



Source: Author's schema based on Nelson & Winter (1982)

Table 1. Hypotheses based on the conceptual relationship between manufacturing and innovation

Stage 1: Growth Stage of new technology	Stage 2: Maturity Stage	Stage 3: Next iteration of PLC
Competitive basis: Product innovation	Competitive basis: Process innovation	Competitive basis: New product innovation to avoid technological obsolescence; also high-level process innovation
Spatial relationship between innovation & manufacturing: **Spatial coupling:** close spatial proximity between designing and producing experimental designs. Potential manufacturers are (or working closely with) the experimental designers.	Spatial relationship between innovation & manufacturing: **Spatial de-coupling:** in open, global markets where production technology can be transferred, economies specialize in comparative advantage. Focus of the industry is on reducing costs, so manufacturing shifts to developing economies. Product innovation is embedded in first-mover economies.	Spatial relationship between innovation & manufacturing? **The conceptual debate:** • **H1: Spatial de-coupling**: continued specialization of activities reinforces comparative advantage of economies to spatially separate innovation and manufacturing. • **H2: Spatial re-coupling:** industrialized economies leverage both indigenous and external innovation efforts to increase product innovation where manufacturing occurs.

Source: Authors, based on insights from Mathews & Cho (2007), Nelson & Winter (1982), and Porter (1990)

3.1.3 The spatial decoupling hypothesis

The spatial decoupling hypothesis posits that there will be a spatial separation between manufacturing and innovation over time. In particular, manufacturing will shift to late-comer (i.e. developing) economies, owing to the lower costs of production in these locations. However, during the next wave of the PLC, innovation will predominantly remain rooted in first-mover economies.

Theoretical support for the spatial decoupling hypothesis can be found in work in evolutionary economic geography (EEG) which suggests that the social, institutional and organizational assets required for innovation at the technological frontier are territorially "embedded" in advanced economies (Morgan, 2004; Mudambi, 2008; Storper, 1997). These economies benefit from knowledge, skills and expertise embodied in domestic actors (ranging from scientists, through to venture capitalists through to lawyers), accumulated through previous experience of innovation and manufacturing (Amin & Thrift, 1992;

Eisenhardt & Martin, 2000). Furthermore, they benefit from agglomeration effects, including synergies and positive spillovers between firms, universities and a range of institutions which are spatially proximate (Coe et al., 2004). Together, this spatial clustering of knowledge-based assets allows first-mover economies to act as important innovation hubs, productively exploiting newly-discovered knowledge through access to skilled labour, supplier linkages and specialised market knowledge (Potter & Watts, 2010). This spatial clustering of knowledge-based assets is especially pertinent in the case of high-level process innovations which require access to advanced research, design and engineering capabilities.

Another key claim of economic geographers, which is especially apposite in the present context, is that it is more difficult for external actors to easily access knowledge that is generated in these innovation hubs (Lagendijk & Oinas, 2005; Morgan, 2004). A large share of this technological knowledge is tacit in nature, underlining the importance of spatial proximity for knowledge exchange and spillovers (Pinch et al., 2003). The lack of codified knowledge makes it difficult for actors to transfer outside the hub, unless they manage to recruit knowledgeable actors from these innovation hubs. It is not impossible for late-comer economies to develop their own innovation systems necessary to undertake processes of learning-by-searching (Fu et al., 2011). However, if first-mover economies continuously undertake learning-by-searching efforts to accumulate more knowledge, there is a higher probability that these economies will "outpace" late-comer economies through continuously building on their knowledge capital (Mudambi, 2008; Porter, 1990; Storper, 1997).

Thus work in EEG provides a conceptual basis to support to the hypothesis that there will be a spatial decoupling of industrial activities in successive cycles. This spatial decoupling occurs because the specific assets that underpin innovation are difficult to imitate and spatially embedded in first-mover economies that first invested and continued to invest in being innovative. The result is that these premier innovation hubs continue to produce product innovations and high-level process innovations and, as a result, are able to capture and retain significant value which arises from the control and ownership of inimitable and rare knowledge-based assets (Mudambi, 2008). Conversely, codified knowledge of production technologies enables the spatial transfer of manufacturing to late-comer economies, namely those with a comparative advantage in production. Innovative activity will take place in these countries, although predominantly aimed at incrementally improving process efficiency, and lowering the costs of production.

3.1.4 The spatial recoupling hypothesis

A second (competing) hypothesis explored in the present chapter is that it may be possible for manufacturing and innovation to become recoupled during the next cycle of product and process innovations. Inspiration for this thesis comes from work, particularly by development scholars, on East Asian economies that achieved high-technology industrialization (Fu et al., 2011; Gereffi & Wyman, 2014). A key insight from this literature is that manufacturing helped leading firms in countries such as South Korea and Taiwan to enter new industries and develop technological capabilities through learning-by-doing. Moreover, spatial proximity to manufacturing facilities provided an opportunity for firms to apply new experimental designs and develop the next set of product innovations (Yeung, 2007).

Countries which pursued a strategy of industrialization via technological "catch-up" (Mathews & Cho, 2007) did not begin by undertaking indigenous innovation to independently learn to produce new technologies. Instead, particular emphasis was placed on technology transfer, often supported by activist state policies. Domestic firms were encouraged to enter industries with high export growth opportunities, particularly at a point of technological maturity when the latest production technologies or dominant designs of technologies could readily be transferred (Mathews et al., 2011). Moreover, taking advantage of their late-comer status, these firms sought to acquire foreign technological knowledge in order to close the technological gap with leading economies. A common starting point for these transfers was licencing, joint production ventures, linkages with purchasers of goods in advanced economies and FDI (Hobday, 1995; Hsu et al., 2007). However, as domestic technological capabilities were deepened through experience of imitating, absorbing and producing foreign technology, late-comers increasingly sought to develop their own innovation capabilities. Hence domestic firms combined experiential learning in manufacturing with knowledge gained through internal R&D and leveraged from multiple global innovation hubs (Fu et al., 2011). Amongst others, this has involved serving as suppliers to leading global firms, participating in co-operative R&D ventures with foreign partners, hiring engineers trained in foreign firms and universities, and acquiring foreign innovation-intensive firms (Yeung, 2007).

A longer-term goal of governments has been to facilitate a transition from industrial catch-up to becoming innovative "fast-followers" (Mathews, 2002), with the capability to develop the next set of product and process innovations. This requires the creation of "national system of economic learning" (Mathews & Cho, 2007) through which local manufacturing firms, research institutions, and even domestic markets move along the learning curve and transition from imitation to innovation. An important part of learning involved in enhancing indigenous innovation capabilities is achieved through experimentation, and the trial-and-error testing of multiple sets of product designs. This, in turn, is facilitated by spatial proximity to manufacturing facilities to apply and test new prototypes (Mathews et al., 2011). An important corollary of these complementarities is that indigenous R&D efforts may well lead to increased innovation in economies that specialize in manufacturing, potentially challenging the dominance of first-mover economies. Indeed, without a significant local manufacturing base to gain valuable feedback, learning and optimise design, first-movers may lose their competitive advantages in innovation over time. The result is that there will be a spatial recoupling of manufacturing and innovation in the next cycle of product innovations.

3.1.5 Previous evidence

The literature therefore provides two competing hypotheses about the relationship between manufacturing and innovation over time – each leading to different conclusions for ongoing debates about FMA in clean tech. The first hypothesis suggests that FMA may endure, at least in terms of innovation, owing to the accumulation of territorially-embedded networks of complementary technological capabilities, actors and institutions. Conversely, the second hypothesis suggests that FMA is only temporary, owing to the ability of certain late-comer economies to progressively develop the innovative capabilities required for the next generation of product and process innovations.

Two streams of previous work shed light into this debate about spatial decoupling and recoupling in clean tech. One stream has examined efforts by various late-comer countries to develop a domestic environmental technology industry, with a particular focus on strategies of technology acquisition and innovation. This case-study literature has documents how, in a relatively short space of time, several late-comers such as China, India and Taiwan have developed the capacity to manufacture renewable energy technologies. Furthermore, whilst recognising that experiences have varied across countries, technologies and firms (e.g. see

Furtado et al., 2011; Wu and Mathews, 2012), the literature also documents how technology transfer has invariably played a pivotal role in these processes (Hansen & Ockwell, 2014; Lema & Lema, 2012; Mathews et al., 2011; Ockwell et al., 2008; Pueyo et al., 2011; Qiu et al., 2013; Ru et al., 2012; Wang et al., 2012). To the extent that the source of many transferred technologies has predominantly been first-mover developed economies, and that transfers have often (but not exclusively) been through market channels, this work provides support for the idea of enduring FMA. However, rather than simply being passive recipients of foreign technologies, studies have also pointed to the growing innovative activity on the part of late-comers. A common theme has been how domestic firms in later-comers have made investments to improve the technological sophistication of their processes and products, move into more valuable parts of the value chain and reduce dependence on foreign technology (Lema & Lema, 2012; Ru et al., 2012). What evidence exists suggests that these efforts have had two important consequences. One is that in certain sectors (e.g. wind), the technological "gap" between the products manufactured in late-comers and first-comers is narrowing, although it remains (Liu & Goldstein, 2013; Zhang et al., 2013). Another is that a greater share of products is the result of indigenous innovation. As an example, Wang et al. (2012) reports that the number of wind turbines available in the domestic market which were developed by Chinese firms grew from 25 in 2008 to 51 the following year, out of a total of 120 types.

A second stream of the existing literature which sheds light on our research question relies on patent statistics to capture the major inventors of clean technology. An advantage of this approach is that it allows comparisons between countries. Most of these studies suggest that the bulk of innovation for clean tech continues to take place in developed economies. In terms of absolute filings, Bierenbaum et al. (2012) show that a handful of economies such as Japan, Germany and the US – which were early-movers in terms of green technologies – have dominated the patenting of green technologies over recent decades. Measured by patent-intensity (i.e. patent filings per capita), the authors find that Germany and Japan emerge as front-runners, with a number of smaller European countries which were again early-movers also emerging as significant inventors of clean tech. Conversely, developing countries have lagged significantly in terms of the filing of patents for green technology, consistent with the spatial decoupling thesis. Similar findings emerge in other studies (Dechezleprêtre et al., 2011; Fankhauser et al., 2013; Lee et al., 2009). This said, there is a trend of rising patenting in countries outside the traditional core of Europe, Japan and the

US. Taiwan and South Korea, two countries which can be categorised as late-comers, are amongst the leading economies in terms of patent-intensity (Bierenbaum et al., 2012). Moreover, China, in particular, is emerging as an increasingly important source of green patents (Bettencourt et al., 2013; Dechezleprêtre et al., 2011).

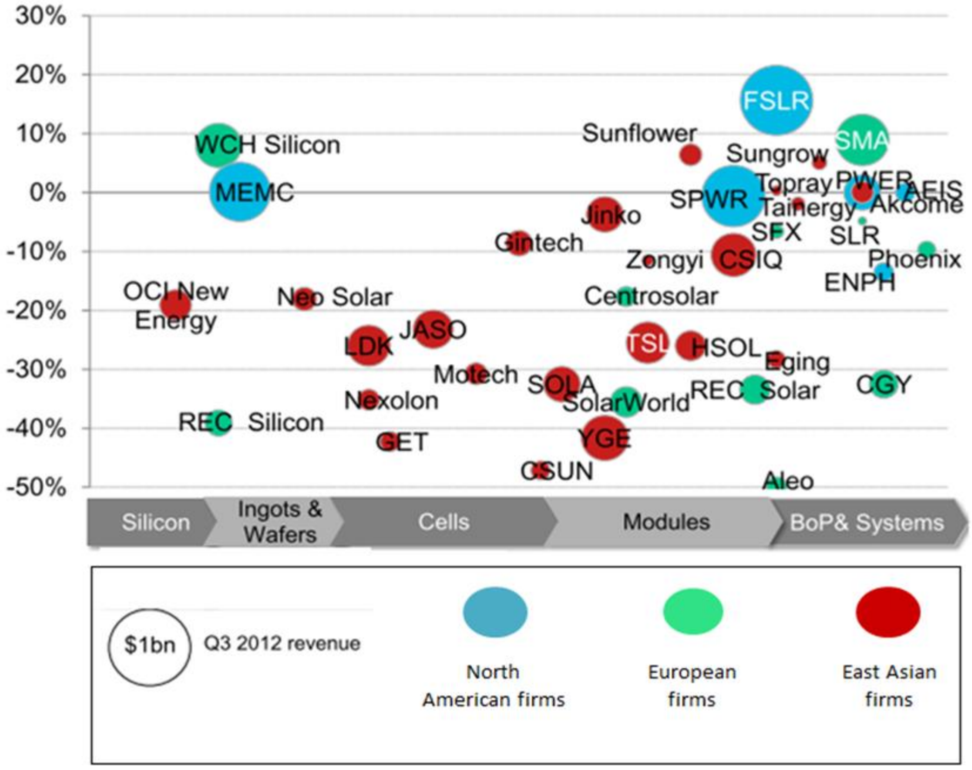
3.2 Research design

3.2.1 Empirical focus

In order to examine the existence of spatial decoupling and recoupling in clean tech, we use the case of solar PV. The solar PV industry has a number of distinctive characteristics which make it a particularly interesting and relevant case in the present context. One is that it is characterised by relatively fast-paced technological change in which innovation continues to be important (Kirkegaard et al., 2010; The Economist, 2013). On the product side, much of this innovation is aimed at improving conversion efficiency of solar cells, although this has gone hand-in-hand with efforts to move towards technologies with lower manufacturing costs. Currently, the dominant ("design") technology in solar PV is crystalline silicon, which is often referred to as a first-generation technology. Crystalline PV technologies account for more than 90% of the global market for solar PV. Many firms that manufacture crystalline PV technologies have suffered negative earnings. This stems from their involvement in parts of the value chain (mostly ingots and wafers, cells, and modules, as seen in Figure 2) which have experienced low and falling market prices as a result of production capacity outpacing market growth. As show in Figure 2, however, firms such as Wacker Chemie and MEMC have achieved positive earnings. The sophistication of their production equipment has meant that these firms can produce silicon and ingot and wafer technologies below the global market price. Hence a major focus of innovation continues to be high-level process innovations which allow manufacturers to improve the efficiency of capital equipment involved in the production of crystalline PV. Many of these innovations have been developed by firms in first-mover economies such as Japan, the US and Germany (Wu & Mathews, 2012).

Another innovation focus is in developing the "next generation" of solar PV technologies that are based on alternative semi-conductive materials (Lee et al., 2009). Prior to the increase in global supply of crystalline PV technologies that occurred after 2007, significant venture capital and private equity (VC/PE) funding was being invested in commercialising these alternative PV technologies. These alternative technologies were attractive because they rely less on silicon material, and have a more integrated production equipment system, potentially allowing production at (per unit) prices that are lower than crystalline PV technologies. As solar PV technologies can be produced from a variety of semi-conductive materials, the possibilities for alternative technologies such as thin-film or organic solar PV technologies are large enough to produce several different types of product innovation within solar PV technologies. As the lack of silicon supply had caused crystalline PV technology prices to increase in the early 2000s, VC/PE investors – particularly in the US – were interested in commercialising these alternative technologies. However "the window of opportunity" for alternative PV technologies appeared to close after 2008, when crystalline prices reduced by 80% between 2008 and 2012 due to the increased global supply. The USA's First Solar (represented as FSLR in the Figure 2) is one of the most profitable solar PV firms because it successfully commercialised and manufactures cadmium telluride technologies below the global price for crystalline PV. Though the level of VC/PE investments into alternative PV technologies has decreased, different countries continue to pursue innovation of these alternative technologies.

Figure 2. Earnings before interest and tax (EBIT) margins of quoted manufacturers by approximate value chain position, Q3 2012



Source: Bloomberg New Energy Finance Note: Labels are ticker symbols or commonly used abbreviations.

Source: Chase (2013)

Another important feature of solar PV is that manufacturing is, to a greater or lesser extent, spatially mobile. The product (i.e. solar PV cells and modules) can be readily transported at a relatively low cost, reducing the importance of physical proximity to markets. Furthermore, the capabilities required to manufacture cells and modules of first-generation, crystalline silicon technologies are not especially high, with off-the-shelf ("turnkey") production technologies available to purchase from international suppliers (Liu & Goldstein, 2013; Mathews et al., 2011). As such, it is a sector which fits with the characterisation of maturity in the PLC, with standardised production technologies making it possible for production to shift to late-comer economies.

3.2.2 Variables and data

Table 1 provides details of our main variables and data sources which fall into two categories: manufacturing and innovation. In order to measure the former, we use data on annual manufacturing capacity of solar PV modules, sourced from Bloomberg New Energy Finance

(BNEF). While capacity and production will not be perfectly correlated, capacity data nevertheless provides us with a comparative measure of the importance of different countries as producers of solar PV.

Three sets of variables are used in order to capture innovative activity, outputs and capacity at the country level. The first variable seeks to measure countries' research output for solar PV. We use the number of publications in scientific journals as our measure of research output, calculated using article counts from bibliometric information downloaded from two of the largest global academic databases: Scopus and Web of Science (WoS). An article was included in the count if it contains the search term "solar photovoltaic". All relevant publications are highly likely to use this "meta-word" to identify their contribution in advancing scientific contributions even within the different technological niches of solar PV. By filtering for publications only from scientific journals, the datasets include research published both by scientific research institutes and firms (who also publish relevant research results to the scientific community). While the use of scientific publications to measure scientific output is well-established in the literature (e.g. see Wagner & Wong, 2012), we do acknowledge that there could be a bias towards journals and articles published in English. As shown later on, however, it is notable that outputs from countries such as Japan, China, South Korea and Taiwan all feature significantly within both Scopus and WoS datasets.

A more serious potential shortcoming of scientific publications is that there is no guarantee that academic research will result in commercially-viable innovations which provide appropriable value-added to economies. Our second variable partially (but not completely) overcomes this problem by using counts of patents that were filed by domestic inventors, and moreover granted. As explained above, the use of patents is common-place in the literature on eco-innovation, not least because they capture the outputs of innovative efforts. Our third set of innovation variables exclusively focus on product innovations. More specifically, they capture countries' contributions to improvements in solar cell efficiency at the technological frontier, otherwise known as "best-in-class." We use two best-in-class measures. The first one is derived from the US Department of Energy's National Renewable Energy Laboratory (NREL), which has compiled data on solar cell efficiencies since 1976. The second one comes from a bi-annual publication of "Solar Efficiency Cell Tables" that are published in the journal, *Progress in Photovoltaics: Research and Applications*. Both sets of data are widely recognised within the global solar PV community as recording the highest confirmed efficiencies of solar PV cells and modules for the different generations of solar PV technologies for any given time period. There are important biases for these data. They do not capture all product innovations, but only new solar PV technologies which displace previous highest confirmed efficiencies, together with details of the inventor/fabricator. Furthermore, they only record product innovations which are sent to leading laboratories (in the US, Germany, Australia, Switzerland and Japan) for testing on a standardised basis, and therefore inevitably under-report innovation the actual level of product innovation (e.g. innovations which improve the durability of modules). In fact, we cannot entirely rule out the possibility of systematic bias across countries, although the "prestige" of being a front-runner means that leading research institutes have motives to disclose results in order to attract – or even sustain – research funding. We also reduce the risk of country bias by using two datasets assembled and published in two different countries.

In the present context, the best-in-class data serve two useful purposes. First, they pinpoint the identity of countries at the forefront of technological advances in conversation efficiency, which is instructive for understanding the distribution of advanced technological capabilities in innovation. Second, because the best-in-class data disaggregate maximum confirmed efficiencies according to different "families" of solar PV, they provide insights into which countries are making investments in "older" and "newer" generations of technology and the "diversity" of their investments. Diversity matters in the present context because it indicates the potential to commercialise alternative technologies – although this typically takes a long time. Furthermore, diversity reduces the risk of becoming locked-into a single technology which may later become obsolete (Martin & Sunley, 2006).

The time spans of the respective datasets differ according to data availability. The datasets that denote research and manufacturing are divided into two different time periods. For scientific research publications and patents, respectively, the first time period is between 1990 and 2004, and the second time period is between 2005 and 2012. The datasets provide a cumulative count of all research articles/patents within the respective time period. The first period covers a time when both first-mover and late-comer economies begin to invest significantly in research/innovation. The second one covers a period when there is a significant shift in manufacturing towards emerging economies.

The BNEF data for manufacturing capacity run between 2005 and 2012 and we take the first and last year for our comparative analysis. Note, 2005 is just one year after the first time period for the innovation datasets, though this can be justified on the grounds that innovation and research often precede manufacturing. BNEF do not have data for all countries. Although Taiwan is a prominent solar PV manufacturer, its data are included as part of the manufacturing capacity of China. We use confirmed operational capacity data for four leading countries in the solar PV industry: China, Japan, the US and Germany. We also use data on India which is selected as an example of another major emerging economy which has entered the clean tech industry (Lema & Lema, 2012).

Table 2. Information on data measures and sources

Industrial activity	Data Source	Time period	Additional notes
Manufacturing: Manufacturing capacity of PV modules (MW capacity)	Bloomberg New Energy Finance (BNEF)	2005-06.2012	1. Annual data on manufacturing capacity for selected countries. Capacity is used as an indicator of the relative size of manufacturing output. 2. BNEF also provides capacities for tier 1 and 2 silicon and solar PV cells.
Research innovation: Scientific publications	Scopus (Elseiver)	Restricted to 1990-2012	1. Relevant publications identified using search term, "solar PV".
Research innovation: Scientific publications	Web-of-Science (Thomson Reuters)	Restricted to 1990-2012	1. Relevant publications identified using search term, "solar PV".
Innovation: Patent filings (absolute numbers)	European Worldwide Office of Patent Statistics	Restricted to 1990 - 2012	1. Countries identified using reported addresses of inventors and firm BVDID addresses. 2. Solar PV patents identified using patent classification code, "Y02E10". 3. Only patents granted included in the dataset, yielding 51,293 patents.
Product innovation: PV cell data (absolute numbers)	National Renewable Energy Laboratory (NREL)	1976-09.2013	1. Total of 205 data points for different PV cells. 2. NREL categorises them within 24 types of PV cells, which are classified in 5 broad family classes. 3. The locations where PV cells were developed verified by additional research.
Product innovation: PV cell data (absolute numbers)	Solar cell efficiency tables from *Journal of Progress in Photovoltaics*	1997-2012	1. Total of 208 data points for both PV cell and modules. 2. Similar type/family classification to NREL. 3. Location where PV cells were developed verified by additional research. 4. Due to limited data availability, the first time period is between 1997 and 2004, and second 2005-2012.

Source: Authors' compilation

3.3 Results: the spatial evolution of solar PV

3.3.1 A brief history

The origins of today's solar PV industry can be traced to the 1950s with the breakthrough development of crystalline silicon PV cells in the US. Early developments owed a great deal to advances in related industries such as semi-conductors and micro-electronics which provided important technological capabilities which could be applied in the emerging solar PV industry (Green, 1990). However, the high costs of solar PV cells meant that market demand remained limited, with their use largely restricted to selected niches such as satellites. Interest in the further development of solar PV technology received a significant boost with the oil crisis in 1973. In order to create alternatives to oil sources, governments in Japan, the US and several European countries significantly increased public funds for R&D into solar PV technology. An important consequence of these investments was increased experimentation, learning and the accumulation of local technological capabilities specific to solar PV. The 1970s also saw Australia emerge as a significant actor in solar PV, with the University of New South Wales assuming a pivotal role as a hubs of research expertise (Effendi & Courvisanos, 2012).

The rise of climate change as a public policy concern in the 1980s and 1990s further accelerated public support for solar PV in various developed economies (Kirkegaard et al., 2010). On the supply-side, governments expanded funding for research, development and demonstration projects which helped to reduce the costs and improve the performance of solar PV. However, of considerable importance was the growth of demand-side initiatives, which significantly expanded the market for solar PV in particular countries (Norberg-Bohm, 2000). Germany emerged as a leader in this respect, through a combination of capital grants for domestic solar installations and feed-in-tariffs (FITs), encouraging new firms to enter solar PV in research and manufacturing and for existing ones to expand their operations in the country (Dunford et al., 2013; Jacobsson and Lauber, 2006). Japan is another country which led in providing generous demand-side incentives for solar PV, including a subsidy scheme for residential solar installations and a quota scheme.

A combination of demand- and supply-side supports therefore played an important role in the development of manufacturing and innovation capabilities in the majority of countries which went onto become significant players in solar PV during the 1990s and 2000s. Yet government policies are not the only reason. First-movers such as Germany, Japan and the US have all been technological leaders in several other high-technology fields, with manufacturing and innovative capabilities in solar PV developing in a context of well-functioning national systems of innovation, together with spillovers from other high-technology sectors (Cooke, 2008). The question addressed in the present research is whether these countries' locally-accumulated capabilities in solar PV have made their dominance in innovation resilient to growing competition from late-comers.

It ought to be noted that several of these apparent "late-comers" have, in fact, had a longer-standing involvement in solar PV. For example, China and India engaged in indigenous R&D during the 1950s and 1960s, and subsequently went onto manufacture solar cells locally. However, domestic technological and innovation capabilities significantly lagged their counterparts in leading developed economies, with manufacturing capacities remaining comparatively small (Dunford et al., 2013; Liu and Goldstein, 2013). Indeed, it was not until the 2000s that late-comers started to become significant players in the solar PV industry, led in particular by South Korea, Taiwan and China (Mathews et al., 2011). In the rest of this section, we trace these dynamics, beginning with manufacturing capacity.

3.3.2 Manufacturing in solar PV

Tables 3-5 show manufacturing capacity in 2005 and 2012 for polysilicon, crystalline silicon PV cells and crystalline silicon PV modules, respectively. We focus on a small number of leading first-mover and late-comer countries in solar manufacturing, as well as India, which is used for illustrative purposes (see below). A number of insights can be drawn from these production data. The first is that the period since the mid-2000s has presided over a dramatic expansion of manufacturing capacity in solar PV. Between 2005 and 2012, global capacity increased by 4,923% and 3,609% for crystalline silicon cells and modules, respectively.
A second observation is that there have been significant changes in the relative share of global capacity contributed by leading countries involved in manufacturing. Most striking is the growth of China. From around one quarter of global capacity of solar cells and modules in 2005, its share had risen to over two-thirds by 2012, making it by far-and-away the dominant producer. The country's dominance in the upstream part of the value chain is less pronounced, accounting for approximately 31% of global capacity in polysilicon production

at the end of our time period, a pattern which Liu and Goldstein (2013) attribute to the higher technological capabilities required to achieve cost-competitiveness in silicon processing.

Another striking shift is the relative decline of Japan which has gone from accounting for just over half of global manufacturing capacity in the mid-stream segment of the value chain in 2005 to 3-4% in 2012. The trends for Germany and the US are somewhat different. Germany's share of global manufacturing capacity was not substantially different at the start of the data period as at the end – with the country actually increasing its relative contribution in cells and modules. The US witnessed a significant decline in its share of polysilicon production, moving from a position of dominance with over half of global capacity in 2005 to accounting for less than one-quarter in 2012. The USA's share increased and declined, albeit not markedly in the case of solar cells and modules, respectively.

A third observation is that the oft-discussed demise of first-mover, developed countries in manufacturing is more relative than absolute. In fact, absolute manufacturing capacity for solar PV in Germany, Japan and the US was actually significantly higher in 2012 than 2005. For example, while Japan's share of solar PV cell capacity plummeted from 53% to 4%, its absolute capacity grew from 551 MW to 2248 MW over our seven year time period. In fact, the declining relative share of leading first-mover, developed economies can largely be explained by the dramatic increase in capacity of China. South Korea has also emerged as a globally significant player – albeit only in polysilicon. The contribution of other late-comer economies has been relatively small, as vividly illustrated by India whose share of global solar PV cell and module production has actually declined.

Hence there has been a significant shift in the locus of manufacturing in the solar PV industry towards China. We proceed in the next sub-sections to examine recent shifts in innovative efforts in solar PV across both first-movers and late-comer economies.

Table 3. Tier 1 and 2 silicon capacity total - tonnes/year

Country	2005 (% of global)	2012 (% of global)*
China	0 (0)	90300 (31)
India	0 (0)	0 (0)
Japan	7500 (25)	21900 (8)
United States	16600 (56)	63500 (22)
Germany	5500 (19)	49800 (17)
Other (mostly South Korea)	0 (0)	62000 (22)
Total	**29600**	**287500**

*Source: *Based on BNEF Q2.2012 Report: figures up to June 2012*

Table 4. Crystalline silicon PV cell manufacturing capacity total, MW/year

Country	2005 (% of global)	2012 (% of global)*
China	253 (24)	34436 (66)
India	20.5 (2)	748.5 (1)
Japan	551 (53)	2248 (4)
United States	0 (0)	1025 (2)
Germany	6 (1)	2462 (5)
Other	211 (20)	11403.5 (22)
Total	**1041.5**	**52323**

*Source: *Based on BNEF Q2.2012 Report: figures up to June 2012*

Table 5. Crystalline silicon PV module manufacturing capacity total, MW/year

Country	2005 (% of global)	2012 (% of global)*
China	373 (28)	33960 (68)
India	66.5 (5)	1588.5 (3)
Japan	688 (51)	1513.5 (3)
United States	90 (7)	1467 (3)
Germany	21 (2)	2882 (6)
Other	103 (8)	8346 (17)
Total	**1341.5**	**49757**

*Source: *Based on BNEF Q2.2012 Report: figures up to June 2012*

3.3.3 Research/innovation in solar PV: Scientific publications

Tables 6 and 7 show results from our analysis of scientific publication counts, respectively derived from two leading search engines, Scopus and Web-of-Science (WoS). Note, our time-frame is longer than for manufacturing capacity, the latter being restricted by the availability of data. We also focus on a larger set of countries, chosen because they account for over 70% of contributions towards solar PV research in both time periods. The publication counts are fairly similar using Scopus and WoS – particularly when it comes to relative shares of the global total.

Several themes emerge from the data. First, the distribution of scientific research outputs are less concentrated than manufacturing capacity, with only a handful of countries accounting for more than 5% of publications in any of the time periods. One plausible explanation is that, compared to manufacturing, the barriers to entry in scientific research are lower allowing a broader range of countries to participate. Manufacturing in polysilicon solar PV is scale-intensive (Dunford et al., 2013), leading to a concentration of manufacturing in particular countries with the capabilities to realise significant production volumes.

Reflecting its long history of research into solar PV, together with underlying scientific strengths, the US appears as the country with the highest number of scientific publications. However, its share of the global total falls between 1990-2004 and 2005-2012, though the absolute number of publications rises. Amongst other developed economies, Japan and Germany are also significant hubs of scientific research outputs, with the UK and France also contributing disproportionately to publications into solar PV technology. Again, their share of the global total generally falls over time, with the relative decline greater in Japan.

Turning to late-comers, China is by far-and-away the major source country of scientific research, followed by South Korea and Taiwan. All three countries markedly increase their share of global publications between the two time periods. In fact, with the partial exception of the US, China eclipses other developed economies in 2005-2012. To take one example: whilst Japan (11%) accounted for a larger share of global publications than China (7%) in the first time period , it was over-taken by China during the second period (7% versus 15%). South Korea and Taiwan similarly catch-up, and sometimes outpace, leading developed economies (Japan, Germany, etc.) other than the US in terms of scientific publications.

Table 6. Scientific publication counts in solar PV research (Scopus)*

Country	TP: 1990-2004 Country Publications	TP: 1990-2004 % of global publications in time period	TP: 2005-2012 Country Publications	TP: 2005-2012 % of global publications in time period
China	739	7%	4823	15%
USA	2095	21%	4525	14%
Japan	1138	11%	2324	7%
South Korea	143	1%	1942	6%
Germany	723	7%	1928	6%
Taiwan	99	1%	1482	5%
UK	504	5%	1306	4%
France	342	3%	1202	4%
Spain	263	3%	1070	3%
Italy	291	3%	1006	3%
Canada	112	1%	600	2%
Australia	259	3%	594	2%
Netherlands	201	2%	469	1%
Switzerland	138	1%	409	1%
Sweden	120	1%	316	1%
Russia	285	3%	258	1%
Total	**7452**	**75%**	**24254**	**75%**

Source: Authors' calculations from Scopus database
*Notes: *Percentages are of the global total in the respective time period.*

Table 7. Scientific publication counts in solar PV research (WoS)*

Country	TP: 1990-2004 Country Publications	TP: 1990-2004 % of global publications in time period	TP: 2005-2012 Country Publications	TP: 2005-2012 % of global publications in time period
USA	1509	21%	6429	18%
China	504	7%	5242	15%
South Korea	124	2%	2892	8%
Japan	788	11%	2425	7%
Taiwan	83	1%	2065	6%
Germany	501	7%	1933	5%
UK	376	5%	1332	4%
France	311	4%	1251	4%
Italy	270	4%	1119	3%
Spain	211	3%	1090	3%
Canada	74	1%	640	2%
Australia	159	2%	547	2%
Netherlands	232	3%	530	1%
Switzerland	112	2%	421	1%
Sweden	102	1%	364	1%
Russia	155	2%	261	1%
Total	**5511**	**78%**	**28541**	**100%**

Source: Authors' calculations from Web of Science database
*Notes: *Percentages are of the global total in the respective time period.*

3.3.4 Innovation in solar PV: Patents

The evidence from scientific publications points to a geographic diversification of major research hubs with China, South Korea and Taiwan all emerging as increasingly important actors engaged in research into solar PV. The picture for patents is slightly different, though similar underlying trends are apparent. Table 8 and 9 respectively show data on counts of patents associated with inventors and firms. We use the same time periods and country selection as was the case for research publications.

A significant increase of inventive activity takes place across the vast majority countries between the two time periods. In terms of developed economies, a large share of patenting is concentrated in just three countries, the US, Japan and Germany. Together, they account for 54% and 76% of patents generated by investors and firms over the first period, 1990-2004. The contribution of other individual developed economies to the global stock of patents is relatively small, typically 2% or less. Moving to the second period, the share of US, Japan and Germany declines to 48% and 62%, as measured by inventor and firm patent counts. However, a closer reading of the data reveals a set of mixed trajectories, with the US increasing its share, Germany broadly maintaining its share, and Japan experiencing a marked decline.

Amongst the late-comers, the most notable trend has been the rise of South Korea as an innovative actor, with the country drawing on its earlier experience in the semiconductors and flat panel displays to enter the solar PV sector (Wu & Mathews, 2012). Accounting for 3% and 1% of inventor and firm patents in the first period, its share significantly expands to reach 15% and 10% over the second. Taiwan's innovative output also increases, reaching 5% and 3%. The dominance of China in scientific research publications is less evident in terms of patenting. Its global share during the second period is 8% and 7% for inventor and firm patents. The former is actually a lower share than for the earlier period, though this decline is relative, with the actual number of patents much higher.

Table 8. Patent counts associated with inventors

Country	TP: 1990-2004 Country patents	TP: 1990-2004 % of global patents in time period	TP: 2005-2012 Country patents	TP: 2005-2012 % of global patents in time period
USA	13296	16%	57672	21%
South Korea	2318	3%	42501	15%
Germany	14844	18%	38320	14%
Japan	16351	20%	37185	13%
China	9030	11%	21369	8%
Taiwan	715	1%	13224	5%
France	1679	2%	7911	3%
Spain	1041	1%	6707	2%
Canada	1112	1%	3447	1%
Italy	615	1%	3370	1%
Netherlands	1494	2%	3198	1%
Switzerland	1403	2%	2862	1%
Russia	3142	4%	2703	1%
Australia	1068	1%	1957	1%
Sweden	990	1%	1310	0%
Total	**69098**	**85%**	**243736**	**88%**

Source: Authors' calculations from PATSTAT database

Table 9. Patent counts associated with firms

Country	TP: 1990-2004 Country patents	TP: 1990-2004 % of global patents in time period	TP: 2005-2012 Country patents	TP: 2005-2012 % of global patents in time period
Japan	17275	47%	25707	24%
USA	6270	17%	22074	21%
Germany	4542	12%	16737	16%
South Korea	520	1%	10326	10%
China	274	1%	7415	7%
France	809	2%	2982	3%
Taiwan	119	0%	2767	3%
UK	1035	3%	2439	2%
Spain	262	1%	2413	2%
Netherlands	808	2%	1426	1%
Switzerland	698	2%	1417	1%
Italy	197	1%	1313	1%
Canada	333	1%	878	1%
Sweden	477	1%	793	1%
Australia	472	1%	759	1%
Russia	56	0%	26	0%
Total	34147	92%	99472	92%

Source: Authors' calculations from PATSTAT database

3.3.5 Innovation in solar PV: Best-in-class products

Patents provide a useful measure of innovative output across both process and product technologies, although aggregate counts provide only a partial indicator of countries who are contributing most to high value-added technological progress. We therefore turn to data on best-in-class solar PV efficiency-enhancing product innovations to gain a more refined understanding of countries at the technological frontier (Tables 10 and 11). The time periods for these data do not map perfectly onto those used for scientific publications and patents, but they provide a good approximation of activity before and after 2005.

Although there are major differences in shares between the two data sources, they both indicate that a small number of first-mover developed economies have been responsible for the vast majority of class-leading product innovations in both time periods. The US in particular emerges as the single dominant source of efficiency-enhancing product innovations in solar PV. Its striking pre-eminence is especially apparent using the NREL data. Australia, Germany and Japan are the two other developed economies which have registered a large share of global product innovations at the efficiency frontier. Note, the former's considerable success in developing single and multi-crystalline silicon PV cells in the 1980s and 1990s was not replicated after 2005. Trends in market share for each of these countries (except Australia) varies across the two sources of best-in-class data. However, taking the US, Germany and Japan, it is notable that the proportion of global product innovation made by this trio increases between the two time periods: from 80% to 85% in the case of *Progress in Photovoltaics* and 77% to 85% for NREL.

Conversely, late-comers are conspicuous by their absence, or at least their comparatively small contribution to advanced product innovations. South Korea, identified earlier as a major source of patents, barely registers any leading-edge product developments. China's contribution is greater over the period 2005-2013, accounting for 4% and 2% of best-in-class innovations depending on the data source. India is similarly the source of a number of class-leading product developments after 2005. Whilst suggestive of an upwards trend in advanced product innovation capabilities, these data nevertheless suggest that late-comers continue to markedly lag behind several first-mover developed economies.

Table 10. *Progress in Photovoltaics*: countries recording best-in-class product innovations

Country	TP1: 1996-2004 Best-in class product innovations	TP1: 1996-2004 % of global product innovations in time period	TP2: 2005-2013 Best-in-class product innovations	TP2: 2005-2013 % of global product innovations in time period
USA	34	37%	64	44%
Japan	13	14%	39	27%
Germany	26	29%	20	14%
China	—	0%	6	4%
Netherlands	1	1%	5	3%
Switzerland	2	2%	5	3%
India	—	0%	3	2%
South Korea	—	0%	2	1%
Spain	—	0%	1	1%
Australia	11	12%	—	0%
France	2	2%	—	0%
Sweden	2	2%	—	0%
Taiwan	—	0%	—	0%
Global Total	**91**	**100%**	**145**	**100%**

Source: Authors' calculations from "Solar Cell Efficiency Tables" versions in Progress in Photovoltaics *journal.*

Table 11. NREL: countries recording best-in-class product innovations

Country	TP1: 1976-2004 Best-in class product innovations	TP1: 1976-2004 % of global product innovations in time period	TP2: 2005-2013 Best-in-class product innovations	TP2: 2005-2013 % of global product innovations in time period
USA	89	69%	48	51%
Germany	7	5%	16	17%
Japan	4	3%	16	17%
Netherlands	1	1%	3	3%
Canada	—	0%	2	2%
China	—	0%	2	2%
India	—	0%	2	2%
Austria	2	2%	1	1%
France	2	2%	1	1%
South Korea	—	0%	1	1%
Spain	—	0%	1	1%
Switzerland	5	4%	1	1%
Australia	16	12%	—	0%
Sweden	2	2%	—	0%
Global Total	**128**	**100%**	**94**	**100%**

Source: Authors' calculations from NREL's "Best-in Class Solar Cell Efficiency" chart.

Additional valuable insight into evolving innovation capabilities and trajectories amongst first-movers and late-comers can be gleaned from their technological diversity in product innovation. Based on NREL best-in-class data, Table 12 shows the best-in-class product innovations for different types ("generations") of solar technologies. Notable is the observation that Germany, Japan and the US exhibit considerable diversity in the range of solar technologies where domestic actors have made significant efficiency-enhancing breakthroughs. Diversity indicates broad-based leading-edge innovation expertise across a range of competing designs in these first-movers. This is important because, from an economy-wide perspective, it guards against lock-into to a single product technology which may become obsolete over the longer-term (Bergek & Jacobsson 2003). Moreover, it suggests countries are "competing for the future", developing the next set of product innovations which provide lasting competitive advantages for the local economy (Rasmusen & Yoon, 2012). The diversity of product innovations is much smaller in late-comers. This does not mean that such countries are not engaged in innovative efforts focused on a wider range of technology, but simply that later-comers have only made leading-edge contributions in a narrow set of technologies. What is interesting to note, however, is that China, South Korea and India have all made class-leading product innovations in "second generation" thin-film cells. This may partly reflect the fact that the scope for further efficiency enhancements in "first generation" crystalline cells is comparatively limited. Yet it is suggests a purposeful effort to engage in innovation for a family of solar PV technologies which are only beginning to be commercialised on a significant scale.

Table 12. Diversity in best-in-class product innovations for different types of technologies

	Crystalline Silicon Cells	Emerging PV	Multi-junction Cells (2 terminal, monolithic)	Single Junction GaAs	Thin Film Technologies	Grand Total
USA	2,729	1,479	5,245	1,643	2,160	13,256
Germany	875	465	581	493	293	2,707
Japan	1,163	529	587		121	2,400
Australia	1,942					1,942
Netherlands		81		496		577
Switzerland		372			49	421
France			204		63	267
Austria		242				242
Canada		211				211
Spain			201			201
China					135	135
India					135	135
Sweden					63	63
South Korea					17	17
Grand Total	**6,709**	**3,379**	**6,818**	**2,632**	**3,036**	**22,574**

Source: Derived from NREL data points

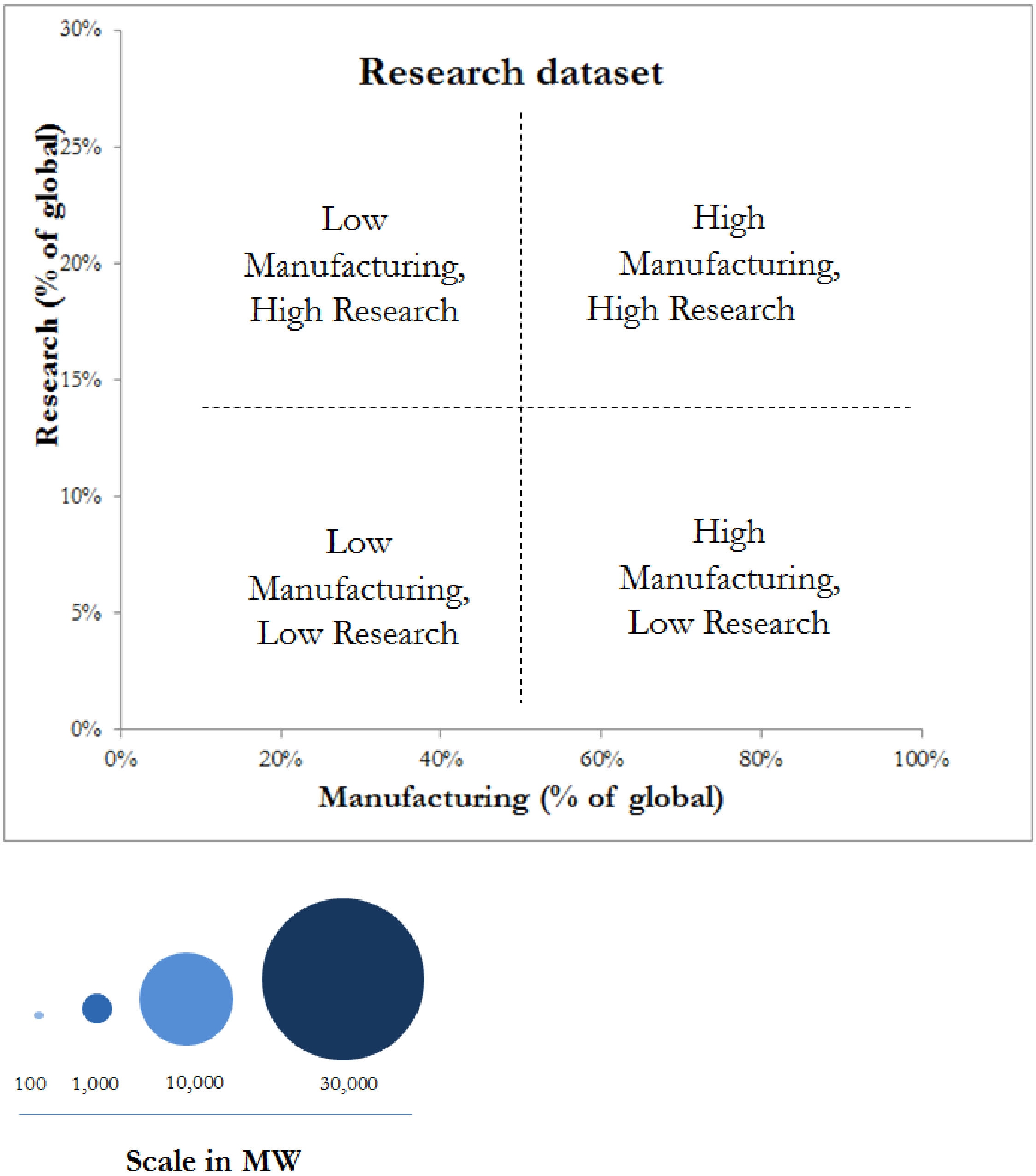
3.3.6 Spatial relationships between innovation and manufacturing

The analysis so far has focused on discrete indicators of either manufacturing or innovation. Yet of particular concern in the present chapter is the dynamic relationship between these two forms of economic activity. In order to better understand this relationship, we use bubble plots to graphically depict several countries' global share of manufacturing and innovation over two respective time periods, shown here by TP1 (2005) and TP2 (2012). As illustrated in Figure 3, the percentage of global innovation is shown on the y axis and manufacturing on the x axis, with the absolute size of PV manufacturing capacity (in MW) indicated by the size of the bubble. We focus on five countries (China, Germany, India, Japan and US) chosen to represent a mix of first- and second-movers in solar PV for which we have confirmed comparative data.

It should be noted that the positions of the countries within the graph provide a relative comparison of countries to each other in terms of their share of the global total for innovation and manufacturing in that time period. It should also be noted that beyond a critical mass of manufacturing capacity, further manufacturing does not matter any longer – especially as it exceeds global demand (see the solar PV chart in Figure 6 in Chapter 2). Nevertheless showing the size of the manufacturing capacity illustrates how much manufacturing capacity has grown for each country – not just for second-movers, but first-movers as well. Presenting the size of manufacturing capacities further demonstrates the importance of innovation over manufacturing – i.e. ensuring economic resilience. Though the industrial capacity of all the countries increases over time as manufacturing technologies become more readily available, it further exposes each country to global supply and demand for what become increasingly globally traded commodities. Therefore success in innovation is needed in order to create more high-value technologies that no other country has produced yet.

In testing our hypotheses, spatial decoupling would be revealed if two conditions held: (a) first-movers retained their dominant position in innovation between TP1 and TP2 whilst losing their large share of manufacturing; and (b) late-comers increased their manufacturing dominance between TP1 and TP2, whilst not experiencing an equivalent (or at least significant) increase in their global share of innovation. Conversely, evidence of re-coupling could be seen if: (c) first-movers lost both their dominance in manufacturing and innovation between TP1 and TP2; while (d) second-movers experienced a significant increase in both their manufacturing and innovation share between the two time periods.

Figure 3. Legend: Interpretation of comparative graphs as % of global total for manufacturing (x axis) and innovation/research (y axis)

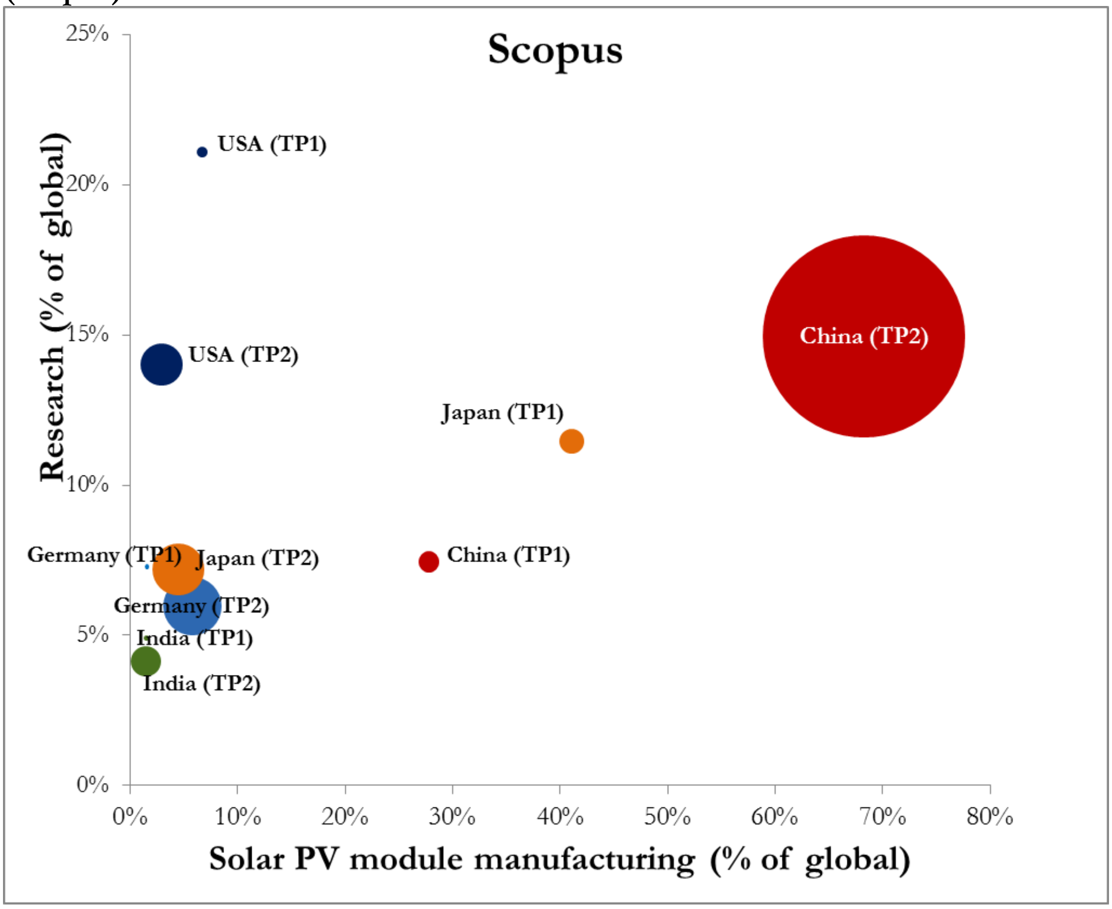


Source: Authors' own schema

Following a similar order as to above, we begin by plotting the share of manufacturing capacity against share of scientific publications, using both Scopus (Figure 4) and WoS

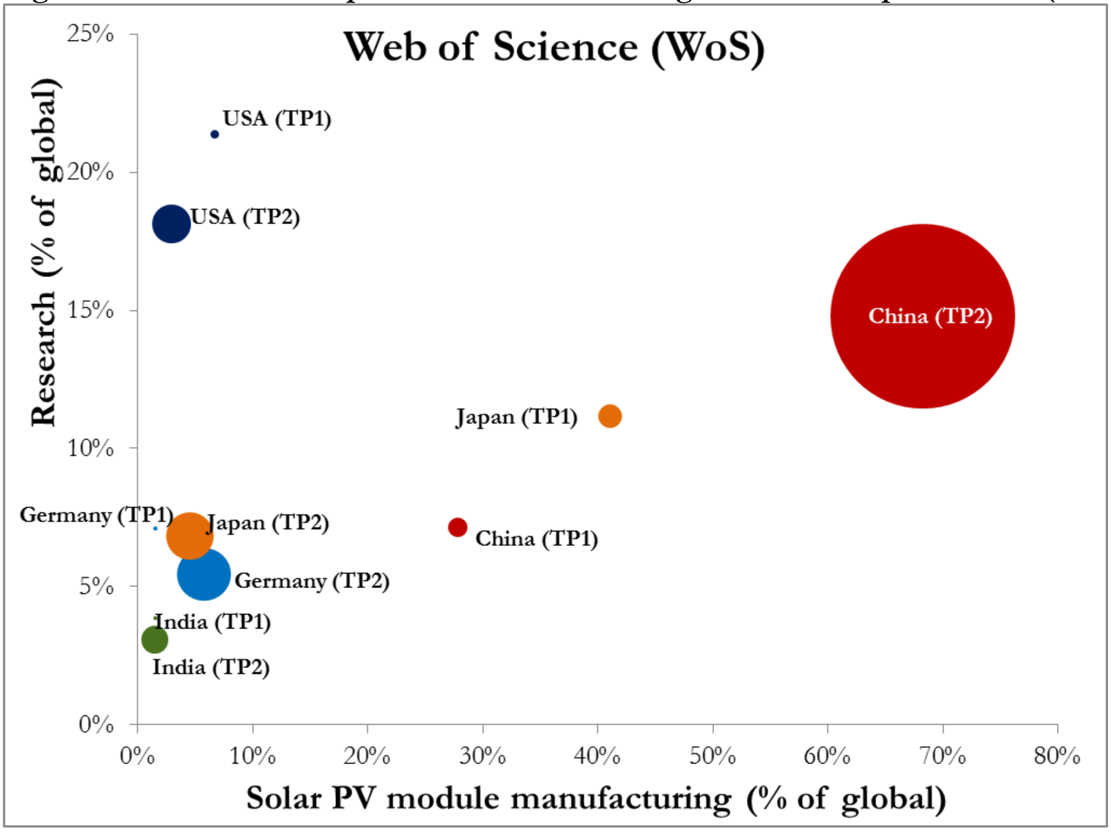
(Figure 5). The first-movers mostly experience a decline in their relative manufacturing between TP1 and TP2, whilst experiencing a decline in their share of global scientific publications, although the respective losses are greater for some countries than others. As a late-comer, China significantly increases both its share of manufacturing output, as well as its share of scientific publications. Taken together, these trends are indicative of a recoupling of manufacturing and research, though an important caveat is in order. The other late-comer, India, shows no trend towards spatial recoupling. Its share of both manufacturing capacity and research remains low in both time periods.

Figure 4. The relationship between manufacturing and research publication (Scopus)



Source: BNEF Q2.2012 Report (figures up to June 2012) and authors' calculations from Scopus database.

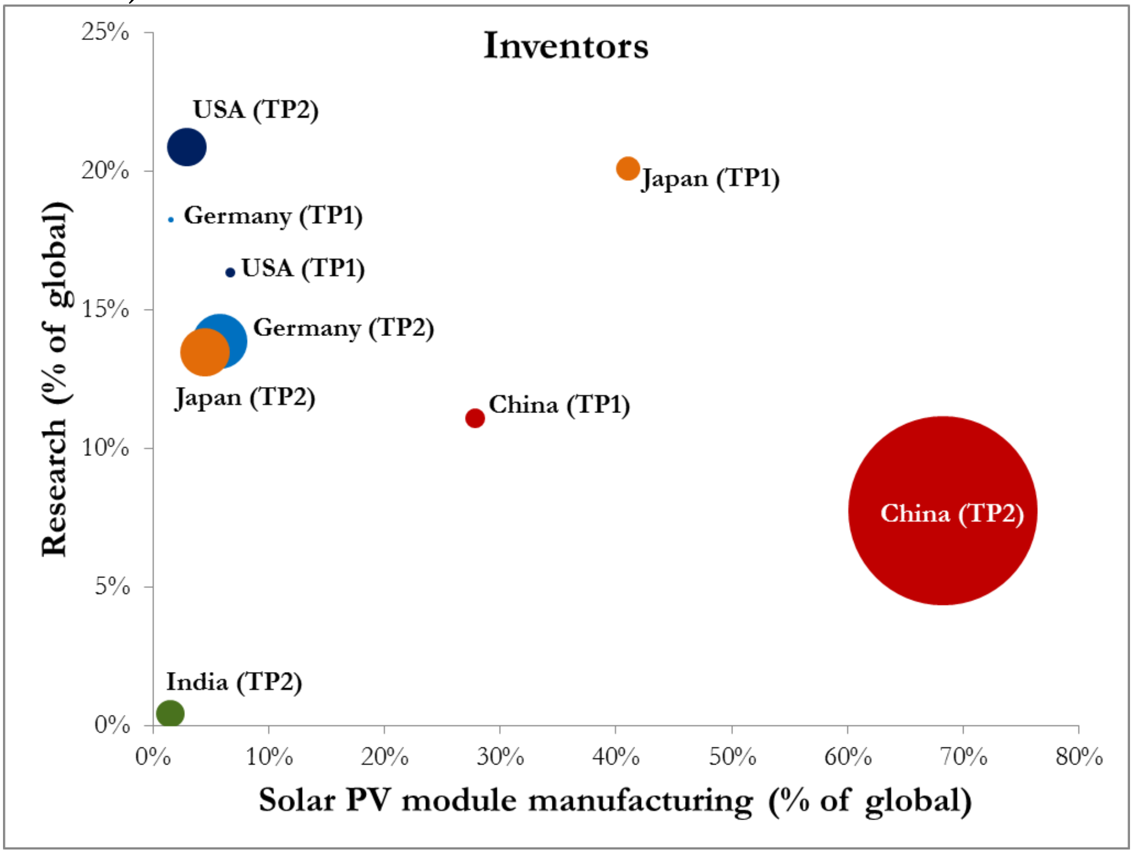
Figure 5. The relationship between manufacturing and research publication (WoS)



Source: BNEF Q2.2012 Report (figures up to June 2012) and authors' calculations from Web of Science database.

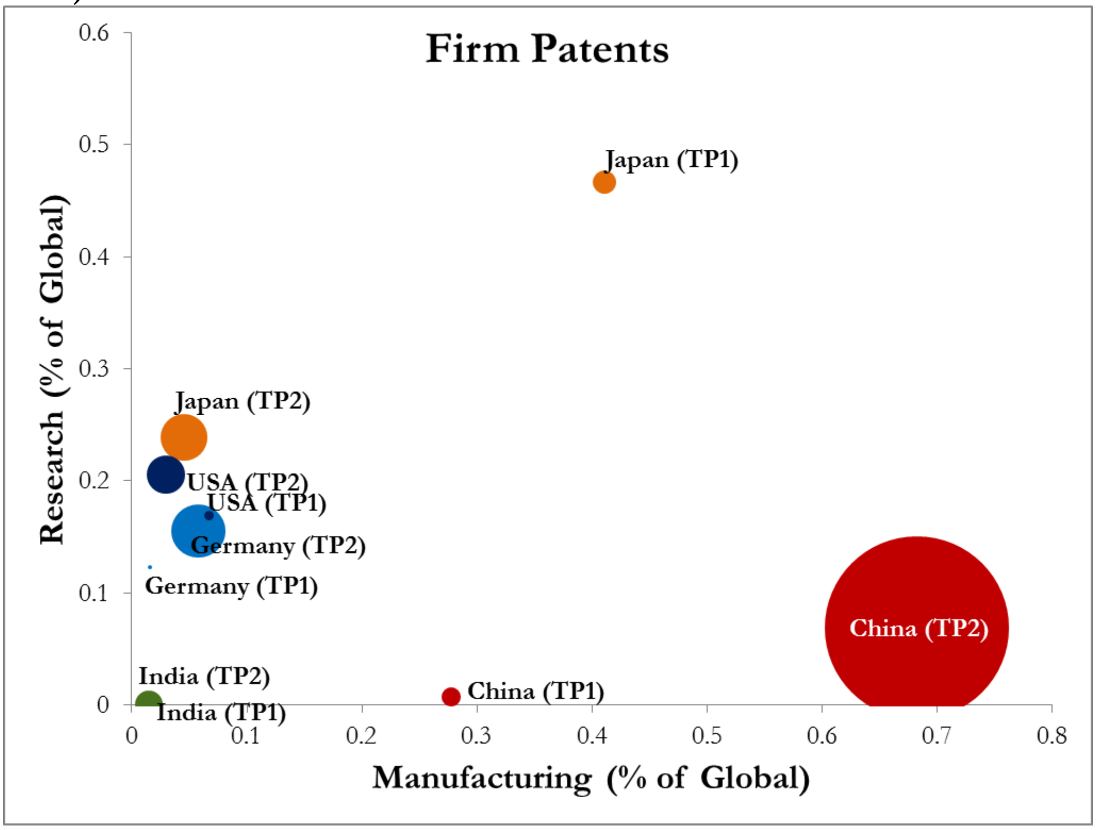
Turning to patents, the evidence for recoupling is weaker, whether measured by inventors (Figure 6) or firms (Figure 7). China's rapid transformation into the preeminent centre of solar PV manufacturing is not matched by equivalent growth in patenting over time. As with research publications, India makes little or no progress in terms of expanding either manufacturing or innovation between TP1 and TP2, such that it remains lodged in the bottom left hand-side quadrant (i.e. low manufacturing, low innovation). Whilst Japan experiences a significant loss of both global manufacturing and patenting share over time, such a trend is far less apparent in the case of Germany or the US, with the latter actually increasing its share of global patenting. One potential shortcoming of focusing exclusively on solar modules is that we do not have data on South Korea which has negligible production in this middle part of the value chain. Yet it is worth noting that, when measured by polysilicon manufacture, it is apparent that the country has both significantly increased its share of manufacturing and patenting in a short period of time consistent with progressive recoupling (not shown graphically).

Figure 6. The relationship between manufacturing and patents (associated with inventors)*



Source: BNEF Q2.2012 Report (figures up to June 2012) and authors' calculations from PATSTAT database.
*Notes: *India TP1 is obscured in the graph, with the country occupying a roughly similar position as in TP2*

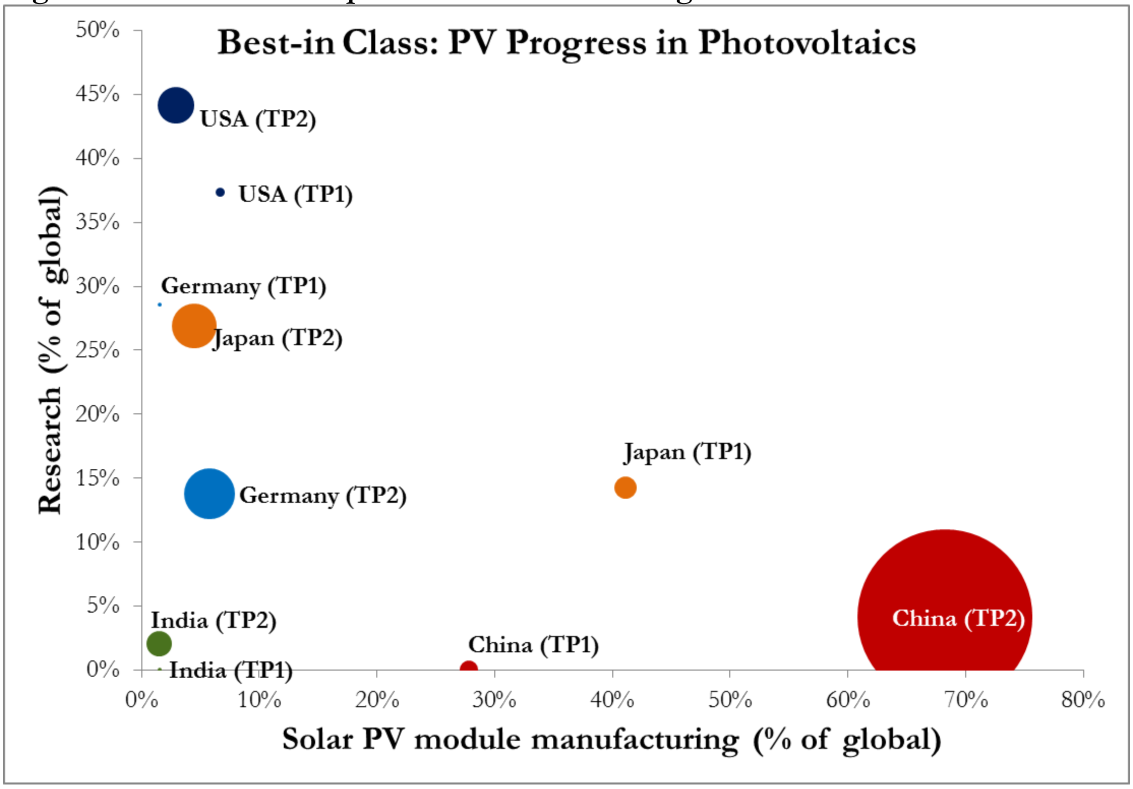
Figure 7. The relationship between manufacturing and patents (associated with firms)



Source: BNEF Q2.2012 Report (figures up to June 2012) and authors' calculations from PATSTAT database.

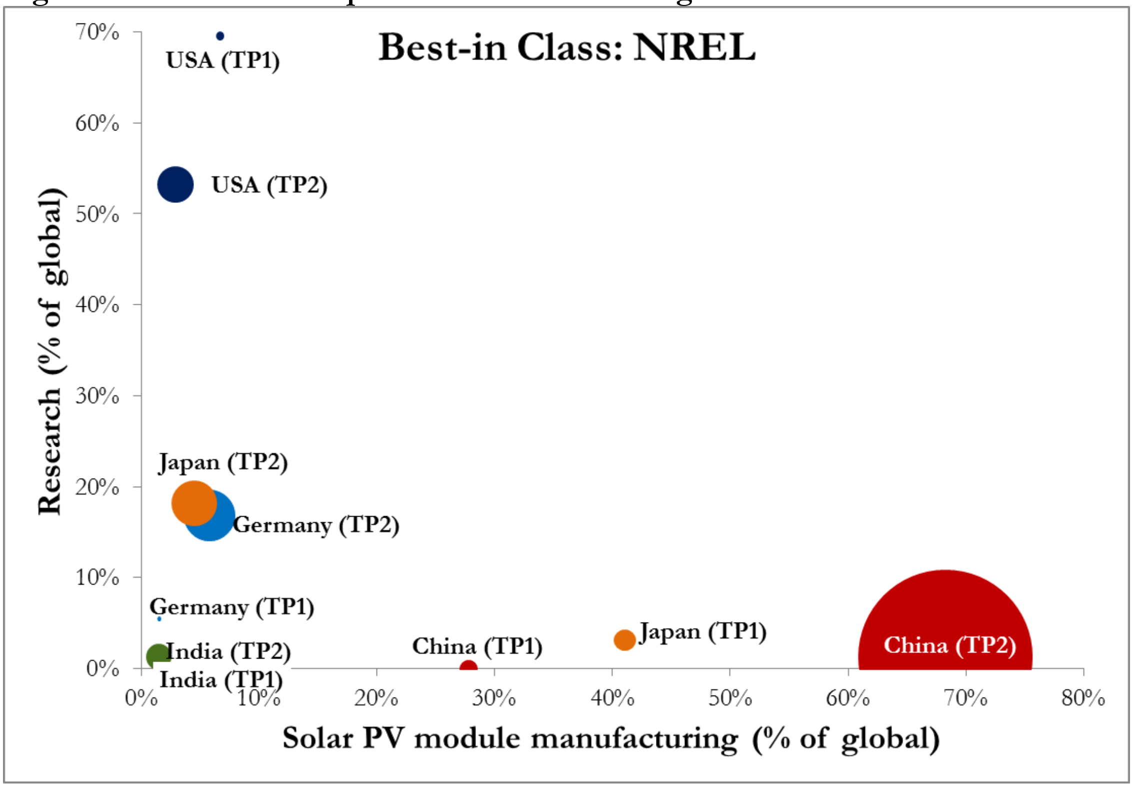
We turn finally to best-in-class data (Figures 8 and 9). There is very little compelling evidence of recoupling. India and China exhibit similar trends as those observed for patenting. Amongst the first-movers, there are some differences, but the overall pattern is one of continued dominance in innovation whilst mostly experiencing a fall in their contribution to manufacturing.

Figure 8. The relationship between manufacturing and best-in class data



Source: BNEF Q2.2012 Report (figures up to June 2012) and authors' calculations from PV Progress in Photovoltaics *journal article series.*

Figure 9. The relationship between manufacturing and best-in class data



Source: BNEF Q2.2012 Report (figures up to June 2012) and authors' calculations from NREL's "Solar Cell Efficiency" chart.

3.4 Discussion and conclusions

This chapter maps the changing spatial distribution of manufacturing and innovation in the clean tech industry using the example of solar PV. Conceptually, our analysis is rooted in the product life-cycle model, which gives rise to two competing hypotheses (spatial decoupling and recoupling) regarding the dynamic relationship between manufacturing and innovation over time. We provide evidence of a dramatic global shift in the locus of manufacturing activity in solar PV away from first-mover economies such as Japan and Germany towards a handful of late-comer economies. Taking advantage of its competitive advantages in manufacturing and ability to acquire technological capabilities in solar PV, China has accounted for the vast majority of recent capacity expansion, particularly in cells and modules. South Korea has also become a significant manufacturer, albeit only in the upstream part of the value chain. Other emerging economies, while increasing their output, have remained relatively small players in the production of solar PV.

Yet this changing centre of gravity of manufacturing has not been accompanied by an equivalent shift in the locus of innovative activities over which, to a greater or lesser extent, first-movers have retained their dominance. In other words, our findings provide support to the spatial decoupling hypothesis, which predicts a growing spatial separation between manufacturing and innovation over time. However, this headline conclusion comes with a number of important caveats, which paint a more nuanced picture of recent dynamics. First, there is evidence of spatial recoupling in the case of scientific publications, where China and South Korea have significantly increased their outputs in both relative and absolute terms. It is however far less evident in the case of patents and especially best-in-class product innovations. Whilst filing a growing number of patents, China is still some way behind Germany, Japan and the US, although South Korea is increasingly part of the "club" of leading patenting economies in solar PV. Neither country is close to challenging the dominance of the main first-movers at the technological frontier of efficiency-enhancing product innovation (Wu & Mathews, 2012). What this would suggest is that catch-up is greater in underlying science (e.g. required for inventive activity), but more partial in the case of applied capabilities required to turn ideas into commercially viable, class-leading products. Another caveat is that a declining share of manufacturing in first-movers has mostly been accompanied by a declining relative share in innovation. The case of Japan is most striking in this regards. Germany and the US have been more resilient to these trends.

A third caveat is that the shift of manufacturing activity is relatively recent. All our findings suggest is that first-movers (and, most notably, China) have been able to upscale their manufacturing capacity faster than their innovation capacity. Stated differently, it would appear to take longer to be successful in innovation than manufacturing, not least because the latter only requires technological capabilities together with capital to invest in plant and equipment. Higher-value forms of innovation which allow countries to move from simply replicating existing designs to developing entirely new ones require well-developed innovative capabilities (Lema & Lema, 2012). Previous work indicates that it may be possible for late-comers to accumulate these capabilities, but that this takes considerable time, effort and the right set of enabling conditions (Dicken, 2010; Fu et al., 2011; Hobday, 1995). The important point is that there is nothing to suggest that China, South Korea or indeed other emerging economies will not become future leaders in high-level innovation. Yet the evidence from our study suggests that this will not happen in the short-term.

Still, without losing sight of these caveats, our findings have a number of wider implications. First, they are instructive for debates regarding the importance of spatial proximity to manufacturing for continued innovative performance (Boschma, 2005; Potter & Watts, 2010; Yeung, 2007). The literature offers a number of compelling reasons as to why, despite advances in information and communication technologies, it might still matter to retain a significant domestic manufacturing base. For example, leading-edge product innovation is known to require considerable experimentation, which benefits from proximity to manufacturing where new designs, material and production techniques can be trialled. Indeed, given the price sensitive nature of the market for solar PV products (Dunford et al., 2013), competitive advantage in the sector requires a close coupling between product and process innovations. Our findings suggest that while late-comers may well benefit from an increased manufacturing base to increase their innovative output, first-comers do not significantly lose their innovative strength against a backdrop a declining share of global manufacturing capacity.

One plausible explanation for this finding lies in our data. The decline in manufacturing dominance of first-movers is relative rather than absolute. The US, Japan and Germany have all increased their total manufacturing capacity. What may count is not simply the global share of manufacturing, but retaining a "critical mass" of local manufacturing, which supplies the necessary feedbacks, learning and synergistic spill-overs. This ties into another related explanation provided by work in economic geography into the factors which render global innovation hubs successful (Hassink, 2010; MacKinnon et al., 2009). After several decades of experience, learning and capability-building, it may be that first-movers have developed well-functioning innovation systems which make them resilient to growing competition from late-comers. Indeed, consistent with this interpretation, several studies highlight how the success of the clean tech industry in first-mover economies can be attributed to clusters of interdependent firms, institutions and social capital, which provide positive externalities (Cooke, 2008; Jacobsson & Lauber, 2006; Pegels & Lütkenhorst, 2014). In the case of the solar PV industry, first-movers such as Japan, Germany and the US continue to retain their advantages in process technology, supplying a large share of the production equipment that is installed in solar PV factories globally.

Our findings also have implications for academic and applied debates about FMA in clean tech (Fankhauser et al., 2013; Huber, 2008; Lee et al., 2009). The past decade has witnessed growing concerns about the domestic economic returns from public supply- and demand-side supports – particularly in the area of renewable energy technologies – which have been provided in developed economies. A particular focus of these debates has been on solar PV, with critics suggesting that price-based incentives such as FITs in Germany amount to a large cross-subsidy to Chinese producers, rather than a fillip to domestic firms. Our findings certainly do not challenge this narrative, at least in the case of manufacturing, with evidence elsewhere confirming that the majority share of the dramatic expansion of solar PV production in China has been exported to supply growing demand in developed economies (Kirkegaard et al., 2010; Liu and Goldstein, 2013). Indeed, to the extent that China has been able to readily acquire the technological capabilities required to manufacture cells and modules, we support the idea that late-comers can take advantage of technological advances in first-movers to gain a competitive lead (Lieberman & Montgomery, 1988; Perkins & Neumayer, 2005).

At the same time, results from our analysis place these concerns in context. They indicate that first-movers such as Germany and Japan may have lost out to China in terms of capturing some of the value-added from manufacturing to supply growing demand. However, they would appear to have mostly retained their lead when it comes to innovation, particularly in terms of their ability to develop patentable technology and leading-edge product enhancements. This is important. As recognised by economists, economic geographers and management scholars, innovation underpins the creation of high value-added and increasing returns to the domestic economy (Aghion & Howitt, 1998; Mudambi, 2008; Storper, 1997). Manufacturing, by contrast, is vulnerable to declining economic returns over time (Ernst et al., 2001).

One limitation of our chapter is that we do not have comparable financial data on the revenues, returns and profitability of the solar PV industry in different countries. Our assertion is nevertheless supported by evidence from other studies. For example, Goodrich et al. (2011) show that the US enjoyed a net trade balance of about US$900 million in 2011 with the China, stemming from the sale of advanced proprietary materials and manufacturing equipment of solar PV product technologies. Chase (2013) demonstrates how many leading East Asian firms – along with European and US firms that participated in the parts of the crystalline PV supply chain that were vulnerable to increases in global supply – have negative margins of earnings before interest and tax (EBIT). However certain American and European companies that were in the high value parts of the supply chain – or a profitable alternative to crystalline PV – do show positive EBIT margins that are above the rest of the industry. Studies have also highlighted how the rapid expansion of solar PV manufacturing in China, supported by government-derived subsidies, has led to over-capacity, falling margins and bankruptcies of high profile firms such as S0075ntech (Liu & Goldstein, 2013; Zhang et al., 2013). Manufacturers in first-movers have not been immune from these pressures and have similarly suffered capacity cut backs, closures and job losses. Yet the important point is that ongoing innovative advantages in first-mover economies provide them with a certain degree of resilience against downward cost pressures for manufactured products arising from comparatively low (technological) barriers to entry in crystalline silicon cells and modules (Liu & Goldstein, 2013).

We therefore conclude by suggesting policy-makers in developed economies should not erroneously read recent dynamics in the global solar PV industry as evidence against the case for early public support for clean tech. Headline statistics about the dramatic shift of the clean tech industry to industrialising Asia are potentially misleading from the perspective of appropriating high valued in the local economy. Our study suggests that early involvement in solar PV – often supported through government policies – did provide enduring first-mover advantages for countries such as Germany, the US and, to a lesser extent, Japan, in terms of innovation. Likewise, for policy-makers in emerging economies, our findings suggest that it may be possible to achieve growth in domestic manufacturing capacity in clean tech. Yet this will not rapidly translate into strong domestic innovation capabilities in the short-term.

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Chapter 4: Accessing knowledge spillovers through international research collaborations: Analysis of solar PV innovation networks

A comparative approach to how the maturity of technologies and the domestic industrial composition affects the propensity for actors to collaborate with domestic or foreign partners.

ABSTRACT. The structure of global innovation networks (GINS) and international research collaborations can highlight the level and quality of knowledge spillovers different countries have – based on their position within these networks and the countries they actually collaborate with. Evolutionary economic geography (EEG) and international development literature implicitly recognises that a hierarchy exists amongst countries with different levels of technological capabilities. EEG highlights how countries with high technological capabilities are those that can engage with innovation at the technological frontier – and can thus restrict international research collaborations between these groups of countries. International development literature recognises that countries with lower technological capabilities undertake research collaborations with countries with high technological capabilities in order to benefit from experiential and knowledge spillovers. Both EEG and international development literature recognise that the 'catch up' nature of these collaborations does not necessarily guarantee that countries' will benefit from knowledge spillovers at the technological frontier. This chapter explores these interactions by studying the evolution of different countries positions within different solar PV innovation networks over two time periods. It also focuses on the research collaboration profiles of Germany, Japan and USA (as first-mover countries) and China (as a late-comer) – – which all have high industrial capacities for solar photovoltaic (PV) technologies. The preliminary results identifies countries with low industrial capacity but high technological capabilities playing a more prominent role in research collaborations for each of these countries with large industrial capacities. This finding is surprising as the current literature has focused on the importance of research collaborations between countries with high industrial capacities – as they share similar challenges in

using research to improve the technological capabilities of the domestic industry. Given this research finding, this chapter considers whether countries with high industrial capacity would prefer to collaborate with countries that they do not compete with in manufacturing but who still have high technological capabilities.

4.1 Introduction

Evolutionary economic geography (EEG) and international development literature both recognise the importance of countries' technological capabilities in not only improving the productivity of domestic industrial capacity, but also in yielding new economic growth opportunities by creating new product innovations. Bell & Pavitt (1997, pp. 85-86) define technological capabilities as "the skills, knowledge and institutions that make up a country's capacity to generate and manage change in the industrial technology it uses". Technological capabilities are distinct from industrial capacity, which refers to the "capital goods, knowledge and labour skills required to produce industrial goods with a 'given' technology" (Bell & Pavitt, 1997, p. 86). This distinction is important as economies with "first-mover advantage" and "late-comer advantage" compete in innovating at the technological frontier. First-mover advantage refers to those countries that participated in the first stage of technological development by innovating and commercialising technologies (Aoyama, Murphy, & Hanson, 2011). Late-comer advantage refers to those economies that have not invested in the initial research and development (R&D) for commercialising technologies (Altenburg, 2008; Ernst, 2000). Instead, they capitalise on the availability of newly developed technology that can be transferred to their own economies (Fan, 2006; Mathews & Cho, 2000). They can then leverage their comparative advantage in producing these technologies at lower costs (Vernon, 1966).

Whilst first-mover countries have demonstrated their technological capabilities in innovating the first cycle of technologies, late-comer countries focus on building their own technological capabilities to compete in innovation in the next cycle (Audretsch & Feldman, 1996; Coe & Bunnell, 2003). Both the EEG and international development literatures recognise the importance of improving the technological capabilities of the domestic economy, as it enables domestic actors to produce high quality technologies, which yield greater economic value because other economies have yet to learn how to reproduce them (Lall, 1994; Pike, Dawley, & Tomaney, 2010; Watson et al., 2014). EEG describes economies with high technological capabilities as being resilient to global competition within a given industry (Hassink, 2010; Pike et al., 2010). The international development literature recognises the need for developing countries with high industrial capacity to escape the "middle income trap" by increasing their technological capabilities to undertake innovation (Aiyar et al., 2013; Ohno, 2009).

An interesting spatial phenomenon that EEG explores is how different economies that compete on innovation also participate in collaborative relationships with innovation (Chompalov, Genuth, & Shrum, 2002; Frenken & van Oort, 2004). This is because as innovation increases in complexity with iterative cycles, it can require the integration of a greater set of resources and knowledge specialisations (Jelinek & Schoonhoven, 1993; Tidd, Bessant, & Pavitt, 1997). EEG highlights that the nature of scientific research – and funders' requirement to demonstrate "novelty" – means that different geographical clusters develop distinct knowledge specialisations (Chompalov et al., 2002; Katz, 1994). Rather than undertake indigenous efforts in achieving the same knowledge specialisation that other countries' have proven specialisations in, an innovation cluster would be more willing to engage in research collaborations with external clusters (Beaver & Rosen, 1978; Gluckler, 2007). International research collaborations thus enable leveraging of each countries' knowledge specialisations to explore potential technological trajectories (Jeong, Choi, & Kim, 2013; Wagner & Leydesdorff, 2005).

Both the EEG and international development literature recognise that international research collaborations thus constitute an important part of knowledge spillovers between countries (Breschi & Lissoni, 2001; Matthiessen, Schwarz, & Find, 2010). The accumulation of national and international research collaborations creates global innovation networks (Glanzel & Schubert, 2005). The structure of global innovation networks not only implies knowledge spillovers between directly collaborating actors, but can facilitate the transmission of these knowledge spillovers to third parties that are connected to either one of these collaborators (Ter Wal & Boschma, 2011, 2009). EEG studies on global innovation networks show that their geographical spread is highly uneven, as it is dependent on the degree of connectedness within these networks, and which countries are connected (Bathelt & Li, 2013; Gluckler, 2007; Matthiessen et al., 2010). The importance of being able to benefit from these knowledge spillovers is that countries can increase their own technological capabilities – thereby not only increasing their competitive advantage in innovation but the productivity of domestic industrial capacity (Aoyama et al., 2011; Dicken, 2011; Ernst, 2000; Henderson et al., 2002).

This chapter is interested in studying the patterns of research collaborations between countries participating in the solar photovoltaic (PV) industry as a way of comparing first-mover versus late-comer dynamics. Chapter 3 demonstrated that more economies are engaging in research of solar PV technologies. This chapter demonstrates that countries which gained first-mover advantage by initially commercialising solar PV technologies still account for a significant proportion of global research activities. However it also demonstrates that China – which entered the industry at a later stage through the manufacture of solar PV technologies – is generally increasing its proportion of global research activities. Given that both first-mover and late-comer countries are engaging in solar PV research collaborations, are there any expectations regarding the patterns of research collaborations amongst countries that also compete in the supply of technologies? What would the implications be for domestic technological capabilities considering their position within global innovation networks, and the profiles of country collaborations?

Both the EEG and international development literature are relevant in identifying key factors that can shape the patterns of research collaborations between countries. The literature from EEG highlights how the nature of innovation requires certain kinds of "proximity" (i.e. similarity) to overcome the friction of spatial distance and facilitate research collaborations (Boschma & Martin, 2010; Morgan, 2004; Ter Wal, 2014). The literature from international development literature that is relevant for this chapter focuses on how developing countries undertake industrial catch up. More specifically, this literature shows that during the initial entry into an industry, late-comer countries will undertake research collaborations with more technologically capable countries – by undertaking research at the technological frontier they can improve their own technological capabilities (Ernst, 2000; Mathews & Cho, 2000; Tang & Hussler, 2011; Zhou et al., 2012). Nevertheless, as they increase their industrial capacity in these technologies, they also leverage their access to domestic industry to increase indigenous innovation (Lewis & Wiser, 2007; Wu & Mathews, 2012).

In order to explore the pattern of research collaborations between first-mover and late-comer countries in the solar PV industry, this chapter gathered global datasets from both peer-reviewed journal articles and patents of solar technologies. Most empirical studies on international research collaborations use only one or the other. However as both scientists and firms undertake collaborations in both types of media, studies which only use one kind of dataset could be biased in their interpretations of the relevance of partnering countries. Considering these biases is especially important as the nature of collaboration for peer-review publications is different from patents (Dasgupta et al., 1962). Whilst the former undertakes scientific research for technologies, the latter engages with research for technologies that seek commercialisation (Gittleman & Wolff, 1995). Thus co-patenting relationships require higher levels of trust between collaborative actors in order to limit knowledge spillovers to potential competitors (Asheim, Coenen, & Vang, 2007; Storper & Venables, 2004). This chapter's interest in comparing research publications with patents is that it can highlight the kinds of knowledge spillovers that occur between countries with different technological capabilities, and what kinds of knowledge flows different countries have access to. So far, no study has used both datasets to investigate this question on research collaborations.

The rest of this chapter is organised into the following sections. Section 2 will review the relevant literature on the patterns of international research collaborations. Based on this literature, this chapter will set up investigative hypotheses to compare the level of connectivity between first-mover and late-comer countries within global innovation networks. Furthermore, it will consider what kind of patterns can be identified from the collaboration profiles of first-mover versus late-comer countries. Section 3 will focus on comparing countries' positions with global innovation networks. Section 4 will analyse the profiles of different countries. Section 5 will then conclude with comments on further research.

4.2 Factors that shape international research collaborations over time

4.2.1 EEG: Patterns of international research collaborations

A branch of EEG is concerned with the development of research collaborations between innovation actors. The motivation for studying research collaborations is that it becomes more prolific in successive product life cycles (PLCs) of high-value technology (a.k.a. "high tech") – highlighting its importance in transmitting knowledge spillovers across regions (Glanzel & Schubert, 2005; Ter Wal, 2014). However different empirical studies demonstrate how these knowledge spillovers improve the technological capabilities of participating actors/regions (Ozman, 2009). These include Sebestyén & Varga's (2012) study of co-patenting with the European Union's 27 countries; Kafouros et al. (2014) study of the improvement of Chinese firms' product sales through research collaborations between national and international university/research institutes; and De Vaan, Boschma & Frenken's (2012) study of survival rates of firms within clusters in the global video-gaming industry. Potter & Watts' (2010) study of lagging regions in the UK demonstrates how lack of access to global knowledge networks negatively affects firms' financial performance in the latter part of the PLC.

EEG develops a framework for analysing the patterns of international research collaborations based on ideas of "proximity" (Boschma & Martin, 2010; Katz, 1994; Ter Wal, 2014). This literature recognises that in spite of a greater number of economies engaging in innovation, it does not necessarily follow that these economies are equally likely to collaborate with each other (Luukkonen, Persson, & Sivertsen, 1992; Ponds, van Oort, & Frenken, 2007). Instead, countries are more likely to undertake international collaborations if they share certain similarities (i.e. "proximity"). The most important of these is spatial proximity (Asheim & Isaksen, 2002). Despite advances in internet and communication technologies (ICT) and decreased costs of long-distance travel, innovative actors still tend to collaborate with others that are spatially proximate to them (Aoyama et al., 2011).

One explanation for the persistence of spatial proximity is shared institutions (i.e. institutional proximity) such as similar cultures, languages and close social networks that reinforce the "neighbour" or "supra-regional" effect of international research collaborations (Ponds et al., 2007). For example, Luukkonen, Persson & Sivertsen (1992), Guellec & van Pottelsberghe de la Potterie (2001), and Ponds et al. (2007) demonstrate how the spatial and cultural similarities of Scandinavian countries enable greater research collaborations within this region. Proximity enables the effective communication and trust that are necessary for research collaborations (Storper & Venables, 2004). The issue of trust also highlights the importance of similarity in intellectual property rights (IPR) regimes, since dissimilarity can discourage international research collaborations (Ernst, 2011; Kafouros et al., 2014).

4.2.2 First-mover versus late-comer countries: Patterns in international research collaborations

How does a country's entry point into industries affect who they collaborate with and their position within global innovation networks? Both the EEG and international development literatures acknowledge that the entry point into these industries can explain differences technological capabilities of various countries (Christopherson, Michie, & Tyler, 2010; Ernst & Kim, 2001; Lall, 2000). Acknowledging the path dependency and cumulative nature of technological capability development, these literatures look at the impact of national innovation systems on each country type's technological capabilities (Lo, Wang, & Huang, 2013; Lundvall et al., 2002). National innovation systems characterise how the process of innovation is shaped by various actors' interactions within domestic institutions as well as domestic and global networks (Freeman, 1995).

EEG argues that countries that are first to successfully commercialise technologies have already developed innovation systems that enhance their technological capabilities (Christopherson et al., 2010; Swanstrom, 2008). The spatial embeddedness of the domestic innovation system allows knowledge spillovers to agglomerate within the local economy, limiting its spread (Asheim & Isaksen, 2002; Maskell & Malmberg, 1999; Storper, 1997). Therefore, there are few economies with the technological capabilities to compete in advancing the technological frontier (Asheim & Coenen, 2006). However, in successive iterations of PLCs, competing at the technological frontier requires a greater variety of knowledge to be integrated into different technological combinations (Ter Wal & Boschma, 2009; UNCTAD, 2005). Certain national economies have developed technological niches that create a narrower, more path-dependent trajectory for the kind of technologies they develop (Boschma & Martin, 2010; Malmberg & Maskell, 1997). However, by tapping into global innovation networks, actors in these economies can access a larger portfolio of knowledge to diversify product development (Coe & Bunnell, 2003; Henn, 2012).

Therefore, the main driver for international collaborations between leading innovation clusters is a recognition of the mutual benefits of such partnerships (Hamdouch & Depret, 2009; Schubert & Braun, 1990). These mutual benefits include knowledge spillovers through interactive learning, shared economic costs of research, and access to larger social networks (Beaver & Rosen, 1978; Coe & Bunnell, 2003; Jeong et al., 2013). These same benefits cannot necessarily be realised by partnering within the domestic economy (Moulaert & Sekia, 2003).

However, first-mover countries are more likely to engage with other countries that have developed similar levels of technological capabilities in order to partner with innovation at the technological frontier (Glanzel & Schubert, 2005; Wagner & Leydesdorff, 2005).

Both the EEG and international development literatures recognise how certain dynamics facilitate international collaborations between countries with different levels of technological capabilities (Amin & Thrift, 1992; Aoyama et al., 2011; Bathelt & Glu, 2003; Dicken, 2011). Both the literatures acknowledge that countries with high technological capabilities attract more research collaborations than those with lower technological capabilities (Gertler & Levitte, 2005; Matthiessen et al., 2010; Storper, 1997). International development literature highlights how late-comer countries can still have comparatively lower levels of technological capabilities despite successfully transferring technologies and increasing their industrial capacity, as they are still developing their own innovation systems. Late-comer countries are motivated to undertake research collaborations with first-mover economies because they see the possibility of increasing their own technological capabilities (Ponds et al., 2007) and because it "raises opportunities for developing country institutions, including firms, to build capacities by learning through interaction with more technologically advanced institutions[…]" (Ockwell, Sagar & de Coninck, 2014, p. 3).

Another literature on global value chains (GVCs) – whose contributions come from both economic geographers and development academics – analyse how actors in first-mover economies increase their research linkages with late-comer countries (Ernst, 2006; Liu & Chen, 2012). These studies explore how firms in developed countries are "offshoring" innovation to developing economy "hosts", where manufacturing occurs (Chen, 2004). The main purpose of offshoring R&D is to create technologies that are suited to the host country's markets (Nieto & Rodríguez, 2011). Another motivation is to undertake R&D that helps actors in host economies to improve their technological capabilities through innovative learning (Qu, Huang, Zhang, & Zhao, 2013). There is no significant indication that foreign industrial capacity is being leveraged to undertake innovation at the technological frontier (D'Agostino, Laursen, & Santangelo, 2012; Haakonsson, Jensen, & Mudambi, 2012). This shows that firms continue with R&D in their home countries due to the spatial embeddedness of innovation processes (D'Agostino & Santangelo, 2012). So although there are greater research linkages between economies with different technological capabilities within global production networks, the balance of research collaboration still favours economies with high technological capabilities (Asheim & Isaksen, 2002; Gertler & Levitte, 2005). It should be noted that literature on international research collaborations within GVCs focuses on inter-firm networks, rather than academic or other types of research collaborations. It is still important to consider the patterns of international research collaborations within scientific research, as it presents other forms of international knowledge spillovers.

Nevertheless, international development literature that studies the development of national systems of learning in industrialising economies – particularly East Asia – demonstrates how these countries also increasingly engage with indigenous innovation. "National systems of learning" refers to the improvement of technological capabilities through the active participation of both the state and firms within domestic networks of research institutions and industrial capacity (Lo et al., 2013; Mathews & Cho, 2000). Firms' R&D branches can leverage their access to industrial facilities to promote technological learning between scientists and engineers (Lazonick, 2004; Wang & Lin, 2012). The government also plays an active role in facilitating these R&D linkages between indigenous research actors (e.g. universities and research institutes) and industries in order to increase indigenous innovation (D'Costa, 2012; Khan & Park, 2011; Khanna, 2008). This access enables actors within the domestic innovation system to quickly test and up-scale production for new cycles of technologies – thereby raising their technological capabilities (Nahm & Steinfeld, 2013).

Mathews & Cho's (2000) comprehensive analysis of the semi-conductor industry in East Asia demonstrates the importance of having a large industrial base to create national systems of learning. Lewis & Wiser (2007) and Liu & Goldstein (2013) demonstrate how large domestic markets for wind technologies – and limited access to foreign technologies – encouraged Chinese firms to leverage their large industrial base, accumulate greater experience, and eventually develop more advanced wind technologies. This literature emphasises how the specific context of East Asian economies has made them less reliant on foreign economies for research collaborations.

4.2.3 Comparative hypotheses of first-mover versus late-comer countries in the solar PV industry

A set of exploratory hypotheses will be set out in this section to compare first-mover and late-comer countries' access to knowledge spillovers through their position within global innovation networks and the research partner profiles of specific countries. These exploratory hypotheses are based on integrating the literature from EEG and international development. The purpose is to have an intellectual starting point to predict where first-mover and late-comer countries' position will be within global innovation networks, and who they will collaborate with over time. Investigating the research collaborations within the solar PV industry is chosen for two reasons. As elaborated in Chapter 3, research for solar PV technologies includes new product innovations and the improvement of existing production processes. Chapter 3 also demonstrated that there is a geographical dispersion of technological niches, creating the conditions for different countries to undertake international research collaborations to leverage these networks. Chapter 3 also demonstrated that first-movers, and increasingly late-comer China, contribute significantly to solar PV research. Therefore studying the research collaborations between countries – and the larger global innovation networks – can enable the investigation of countries' access to international knowledge spillovers.

The first investigation hypothesis is that first-mover countries will tend to be the most central in the network, as the recognition of their high technological capabilities attracts research collaborations with other first-mover as well as late-comer economies (Bathelt & Glu, 2003; Matthiessen et al., 2010). This hypothesis is supported by the literature from both EEG and international development. Nonetheless, EEG studies show that from the perspective of these central countries, they are more likely to collaborate with other similarly advanced countries than with countries that have lesser technological capabilities (Choi, 2011; Guellec & van Pottelsberghe de la Potterie, 2001; Leydesdorff & Wagner, 2008). These findings corroborate the literature that theorises an hierarchical structure to global innovation networks (Choi, 2011; Coe & Bunnell, 2003).

This chapter also investigates how these dynamics change across two different time periods of the solar PV industry. These time periods are delineated by China's rise to prominence in solar PV research, prompting the investigation of who they undertake research with. The hypothesis from EEG is that first-mover countries such as the USA, Japan and Germany are more likely to collaborate with each other in the first period than with a late-comer economy such as China. However, their propensity to collaborate with late-comer economies can increase in the later time period as the latter's research levels increase. For China, it is likely that research collaborations within the country will increase over both time periods. This hypothesis supports the international development literature on East Asian economies, which notes that domestic actors increasingly rely on local resources to engage in indigenous innovation (Fan & Hu, 2007; Tang & Hussler, 2011). However, as China becomes more prolific within solar PV research, it is expected that its profile of international research collaborations will continue to include leading innovation clusters (Kim & Tunzelmann, 1998; Wu & Mathews, 2012).

This section has attempted to integrate the literature from EEG and international development to create exploratory hypotheses that compare first-mover and late-comer countries' access to knowledge spillovers in global innovation networks, and patterns of international research collaborations in the solar PV industry. Section 3 will analyse countries' relative positions within global innovation networks, with a particular focus on the "centrality" measures of Japan, Germany, the USA, and China; section 4 will analyse their specific research collaboration profiles. These four countries were chosen because they have large industrial capacities. Therefore increased domestic technological capabilities gained through domestic and international knowledge spillovers are more likely to directly benefit their domestic manufacturing base.

4.3 Analysing countries "centrality" within global innovation networks

4.3.1 Applying measures of "centrality" to compare countries' positions within global research networks

This section applies "centrality" measures, developed by network theories, to analyse different countries' access to knowledge spillovers through international research networks in the solar PV industry (Morrison et al., 2014; Ter Wal & Boschma, 2009). Network theory analyses the relationships between different nodes in a structure, which cumulatively form a network (Hansen, Shneiderman, & Smith, 2010). In this case, the relationships are signified by the pairs of countries that undertake collaborations with each other; the nodes refer to the countries themselves. Network analysis can thus be used to compare how well-connected different countries are to all the others in the research network, or their "centrality" within the network (Marsden, 2002). Network structures demonstrate that some unrelated countries may nevertheless have indirect access to others through a mutual connection with centrally connected countries (Everett & Borgatti, 2005). The most central countries have the greatest access to information within the network, but also the greatest role in disseminating information to other countries (Wagner & Leydesdorff, 2005).

These measures of "centrality" can thus be used to study different economies' access to knowledge spillovers through their participation in research collaborations with different countries. Four different measures of centrality are used to compare countries' position within these networks (Hansen et al., 2010). The first is "degrees", which refers to the number of countries (including itself) with whom actors of that country have undertaken research collaborations. The second is "betweenness centrality", which calculates how certain countries act as a "bridge" between others that would otherwise not necessarily be connected to each other. Countries with high "betweenness centrality" can thus receive and disseminate the greatest amount of information from and to other nodes in the network. Their absence can cut off other nodes in the network. Their centrality to 'remote' countries in the network also ensures that they receive proprietary information from these countries that other countries are unlikely to access. The next measure that will be used is the "eigenvector centrality" measure, which calculates how well connected a country is to other well-connected countries involved in research collaborations. "Eigenvector centrality" can thus be used to compare where countries are positioned within the hierarchy of research network relations. These different measures of centrality are useful in comparing how easily countries can access not only a broader portfolio of knowledge, but a high quality of knowledge as well (Ter Wal & Boschma, 2009).

In order to undertake an in-depth analysis of how countries' positions changed within the global innovation networks for solar PV over two time periods, this research restricted the number of countries included in the network to 16. It justifies this position as these 16 countries cumulatively contribute to over 70% of the global total of research output in each dataset (as can be seen in Chapter 3). Furthermore it is important to keep the number of countries in each time period constant in order to enable comparisons of countries' centrality within the network in each time period (Luukkonen et al., 1993). The first time period (1990-2004) represents the early stage of large-scale commercialisation efforts of solar PV technologies by first-mover countries. Japan, and even China, had a comparatively large industrial capacity for solar PV at this time (although China's export of solar PV technologies to the global market only really increased in the second time period). The second time period (2005-2012) represents an inflection point where late-comer countries – especially China –

increased their industrial capacity to a point that surpassed first-mover countries. In this case, China overtook Japan in terms of solar PV technology manufacturing.
International research networks are derived by identifying all the country affiliations of different actors that have collaborated on the same research publication or patent. The research publications were identified by searching for "solar photovoltaic" in the two major academic databases of Scopus and Web of Science (WoS) – filtering for scientific publications. Each dataset yielded over 22,000 publications between 1990 and 2012. Authors' country affiliations were determined using the Scopus dataset, and their institutional affiliations were taken from the WoS dataset. The patent datasets are derived from the European Patent Office's Worldwide Patent Statistical Database (PATSTAT), which has compiled global patent data for solar PV technologies, identified under the patent classification code "Y02E10". The 51,293 patents used in the analysis are those submitted by either firms or inventors, and which were granted as patents in the years between 1990 and 2012. Three different types of patent research networks were identified based on collaborations between: (1) inventors, (2) firms, and (3) firms and inventors.

The purpose of using these different networks is to triangulate the evidence that delineates the structure of global innovation networks for solar PV technologies. As will be seen in the next sub-section, networks identified in research publications are very different from those associated with patents. In comparing these networks, this chapter provides spatial evidence for the discrepancy between scientific collaborations and those with more industrial applications. However, this chapter acknowledges that both of these research collaboration types only represent formal networks, represented through codified information (Ernst & Kim, 2001). Therefore, this chapter potentially represents only a subset of global innovation networks, but acknowledges that informal, social networks can also enable knowledge spillovers between countries (Coe & Bunnell, 2003; Østergaard, 2009; Saxenian, 2002). Nevertheless, analysing this codified information is still useful as it represents the outputs – and hence evidence of knowledge spillovers – between different countries.

4.3.2 Comparing countries' centrality within solar PV research networks

The following figures not only show the research collaborations between countries, but each country's position within these figures represents different dimensions of centrality. The NodeXL software application was used to calculate countries' centrality measures, whilst also delineating the connections between countries within the different quadrants of these figures. The purpose of these graphs is to provide a visual representation to enable comparisons between countries. Figure 1 is provided as a guide to interpreting the comparisons between countries based on their positions in the graph. Countries in quadrant 1 in the top right corner of the graph (Q1) are those that are highly connected, and can thus serve as a bridge for less connected countries. Countries quadrant 4 in the bottom right corner (Q4) are connected to many countries, but their connectivity is similar to other countries in this quadrant (in other words, they receive the same level of knowledge spillovers as other countries with same number of degrees). Countries in quadrant 3 in the bottom left corner (Q3) are the least connected, and require other countries to help connect them to the wider network. In other words, these countries are the least central in the network and are the least likely to benefit from knowledge spillovers. Quadrant 2 (Q2) refers to countries that undertake international research collaborations with few countries, but their connections to "remote" countries enables them to act as an effective bridge to the broader network. As can be seen, there are no countries in Q2. It should be noted that the size of the point representing each country denotes their eigenvector centrality– in other words, the country's position within the global hierarchy of research collaborations. The thickness of the lines (known as edges) refers to the number of collaboration between countries. When there are "circular loops" around a country, it represents the amount of intra-country research collaboration; this is distinct from the country "point" which represent eigenvector centrality.

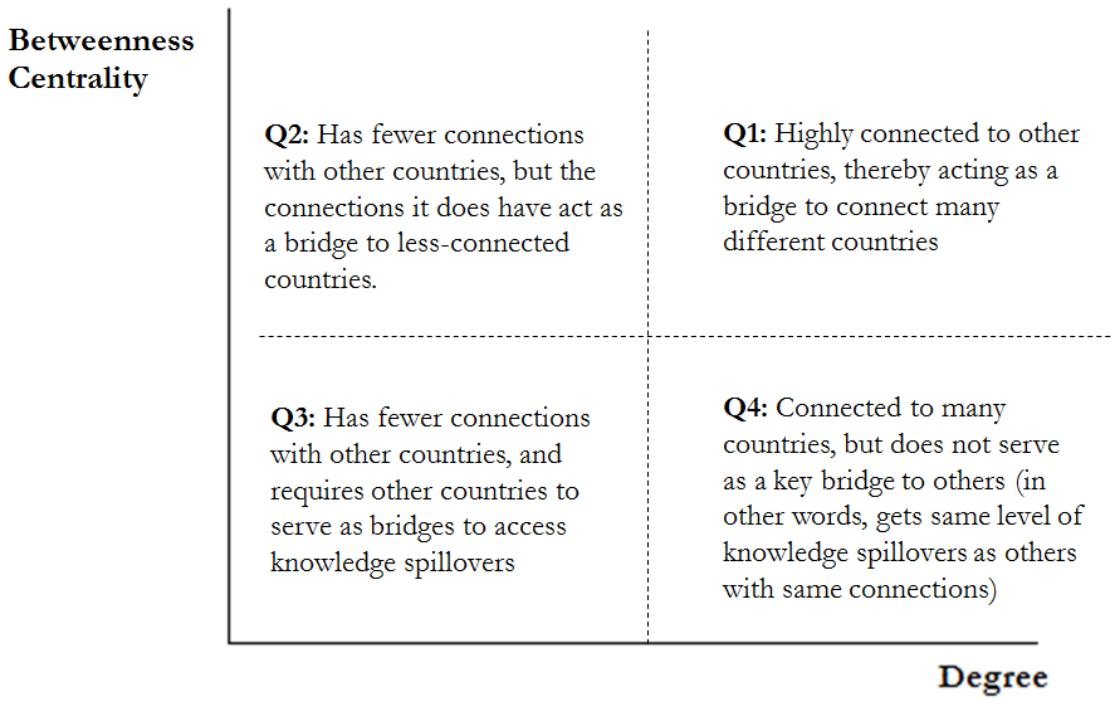
Figures 2 to 6 thus delineate the structure of research networks for each research dataset in each time period. The tables that have the actual centrality values of countries in each time period can be found in Appendix 1. Whilst all 16 countries are represented in most graphs (the UK does not appear in the *Inventors* network graphs because of lack of patents), this section will focus on comparing the centrality positions of Japan, Germany, China and the USA. In looking at all 5 datasets in each time period, it does not appear that the countries' positions within the graph have changed drastically over time. The USA has a high number of degrees and high "betweenness" and eigenvector centralities in both time periods – representing their centrality in both research and patent networks. Germany occupies a similar position in all five graphs, though it has a much lower "betweenness centrality" than the USA. This may indicate Germany's propensity to collaborate mostly with other well-connected countries within the network (particularly European countries) – reflecting its high eigenvector value within the networks.

These charts reveal some interesting findings, especially with regard to Japan and China. In comparison to the USA and Germany, Japan has fewer collaborations with other countries, and has lower "betweenness" and eigenvector centralities. Studies by D'Costa (2012), Luukkonen et al. (1992) largely show that Japan tends to be more insular with its research collaborations, partly due to its highly unique culture and language, but also because it has strong domestic linkages between domestic firms and research institutes. However what is more striking is the difference in China's position in research publications relative to patent networks. Whilst China has higher measures of centrality in research publication datasets (in both time periods), it is less connected and central for collaborations on patents. This difference does not just pertain to China, but also to other countries such as Australia, Sweden, Spain, Italy, and South Korea.

What is very interesting to note is the centrality of Australia, and Switzerland in these research networks. In fact, Australia has higher centrality measures within scientific research publications (see Appendix Tables A1 and A2), whilst Switzerland is higher in patent collaborations (see Appendix Tables A3, A4, A5). In studying the solar PV research community, two important factors can explain these findings. In the case of Australia, it achieved one of the longest-standing world records in the early 1990s for developing the highest crystalline PV cell efficiency within a laboratory setting. This attracted funding from both the Australian national government and British Petroleum (BP) to establish the Australian Centre for Advanced Photovoltaics. This centre attracts prominent international solar PV researchers interested in advancing crystalline solar PV. The Centre also edits one of the most prominent solar PV journals, *Progress in Photovoltaics: Research and Applications,* which publishes the bi-annual results of the world's best-in-class recorded cell efficiencies. The centre is also a major school that attracts students from around the world to engage in solar PV research, thus developing international social networks. In the case of Switzerland, its prominence can be explained by its high technological capabilities in the semi-conductor industry. Switzerland is an important exporter of production equipment that produces different components along the value chain for crystalline PV technologies. Therefore Switzerland's high centrality in patent networks demonstrates its status as an innovation hub for the industrial side of solar PV research.

These findings demonstrate the importance of considering what types of research different countries engage with. Whilst scientific research networks show a more interconnections between countries, patent networks still show both spatial and institutional similarities. The interconnections between countries can be measured by "graph density", which refers to the number of collaborations between countries divided by the total number of possible collaborations, based on the number of countries in the network. Therefore high ratios demonstrate greater connectivity between all countries in the network. Whilst the density of networks increases over time for both types of research, the density for patents is lower than scientific collaborations in both time periods. This demonstrates that whilst late-comer countries like China can more easily benefit from knowledge spillovers through scientific research, they may not necessarily benefit to the same degree from knowledge spillovers in early stage commercialisation activities – as represented by patent networks.

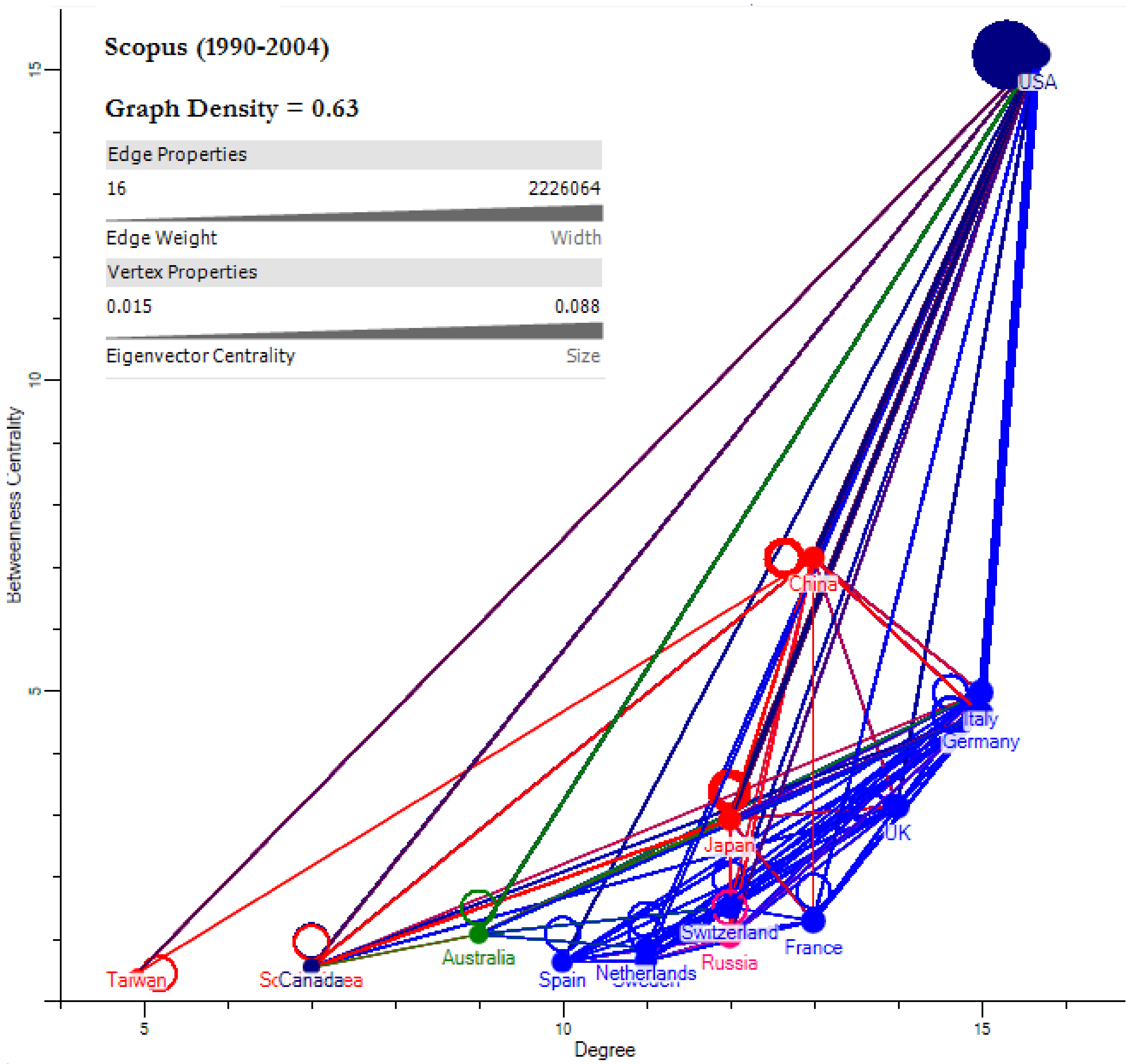
Figure 1. Understanding positions within the figures



Source: Author schematic

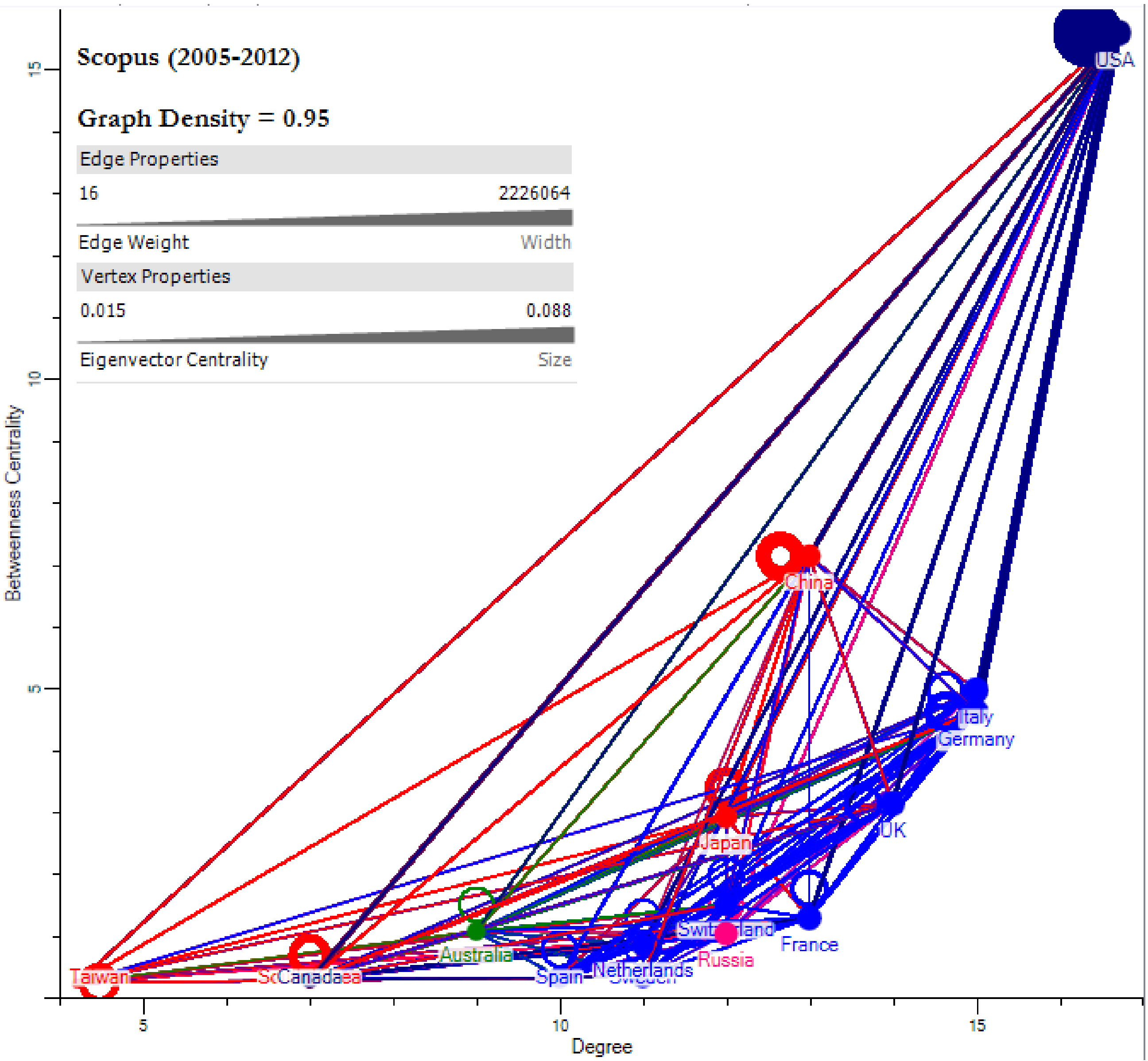
Figure 2. *Scopus*: International research collaborations in different time periods

Figure 2A: *Scopus* co-author research collaborations (1990-2004)



Source: Author's derivation from solar PV author networks from Scopus database.

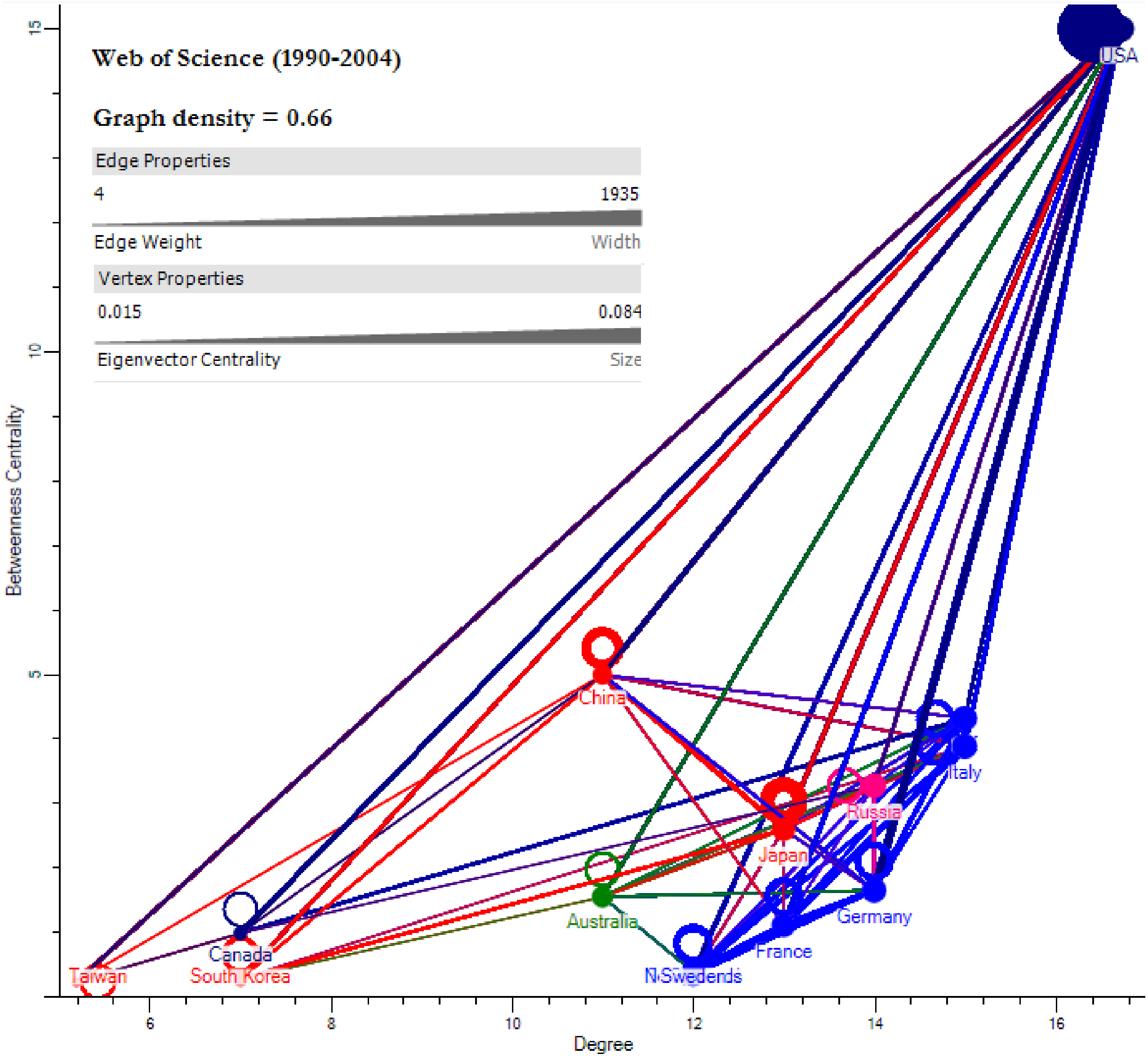
Figure 2B: *Scopus* co-author research collaborations (2005-2012)



Source: Author's derivation from solar PV author networks from Scopus database.

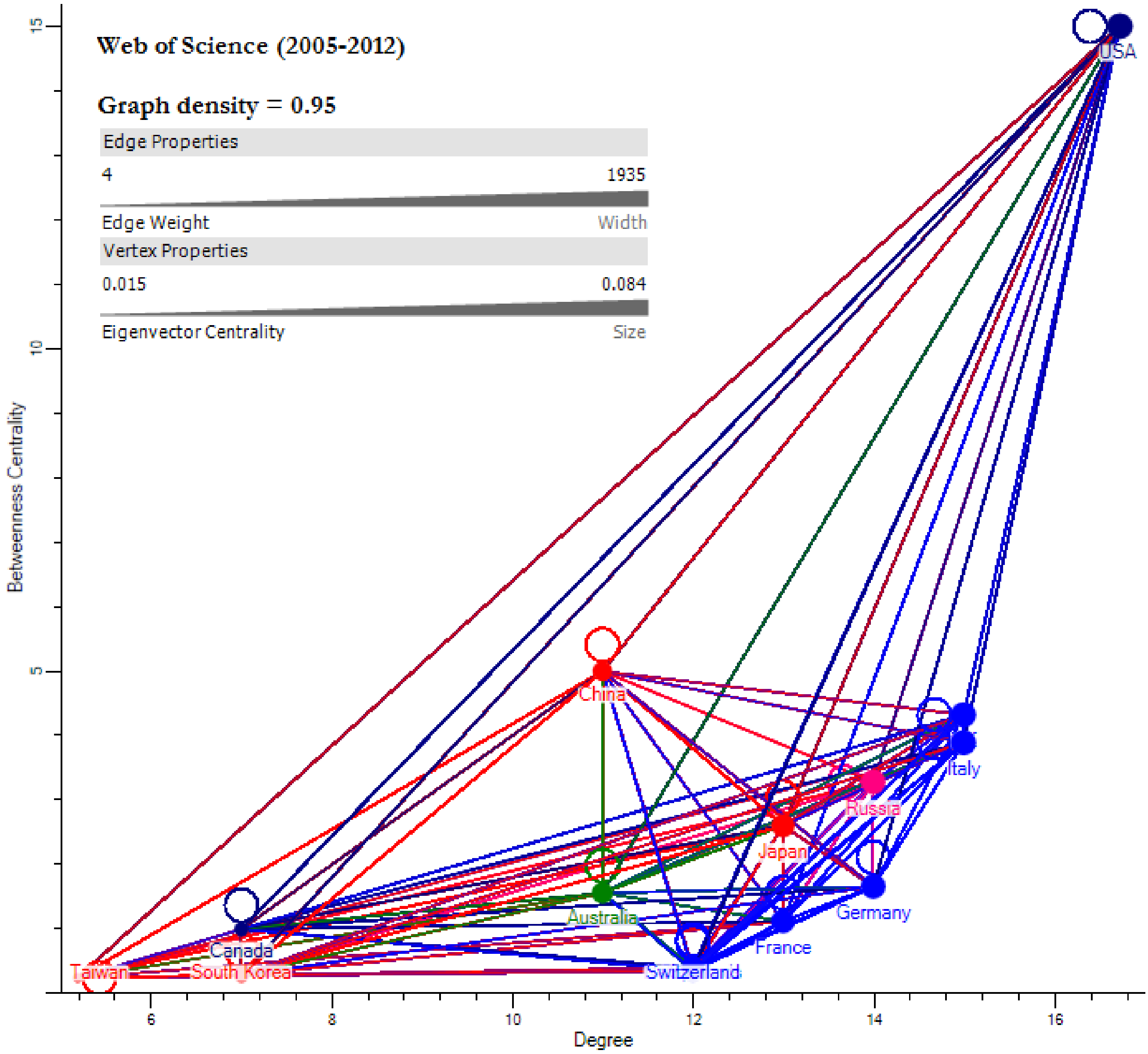
Figure 3. *Web of Science*: International research collaborations in different time periods

Figure 3A: *Web of Science* co-author research collaborations (1990-2004)



Source: Author's derivation from solar PV institutional networks from Web of Science database.

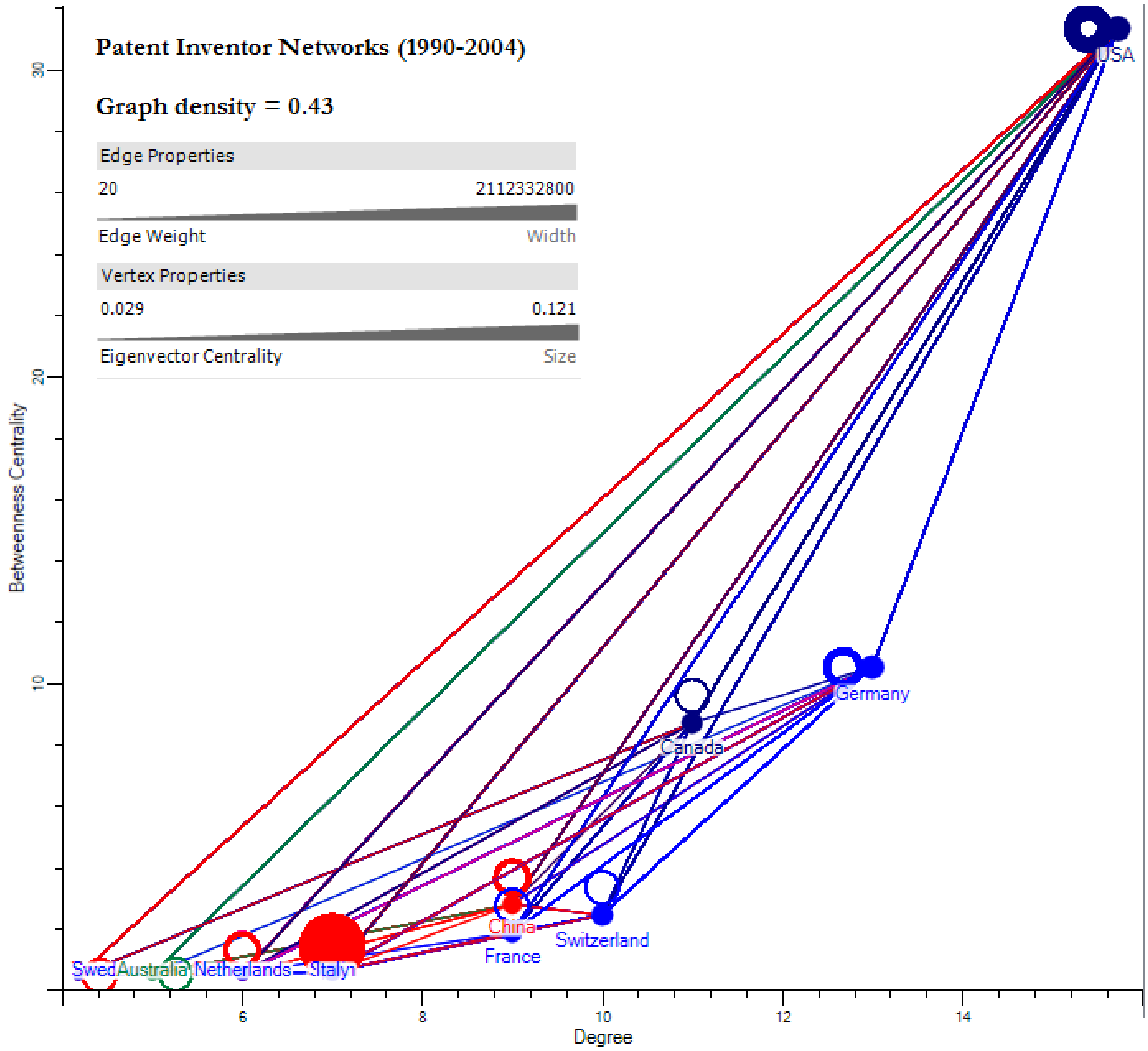
Figure 3B: ***Web of Science*** **co-author research collaborations (2005-2012)**



Source: Author's derivation from solar PV institutional networks from Web of Science database.

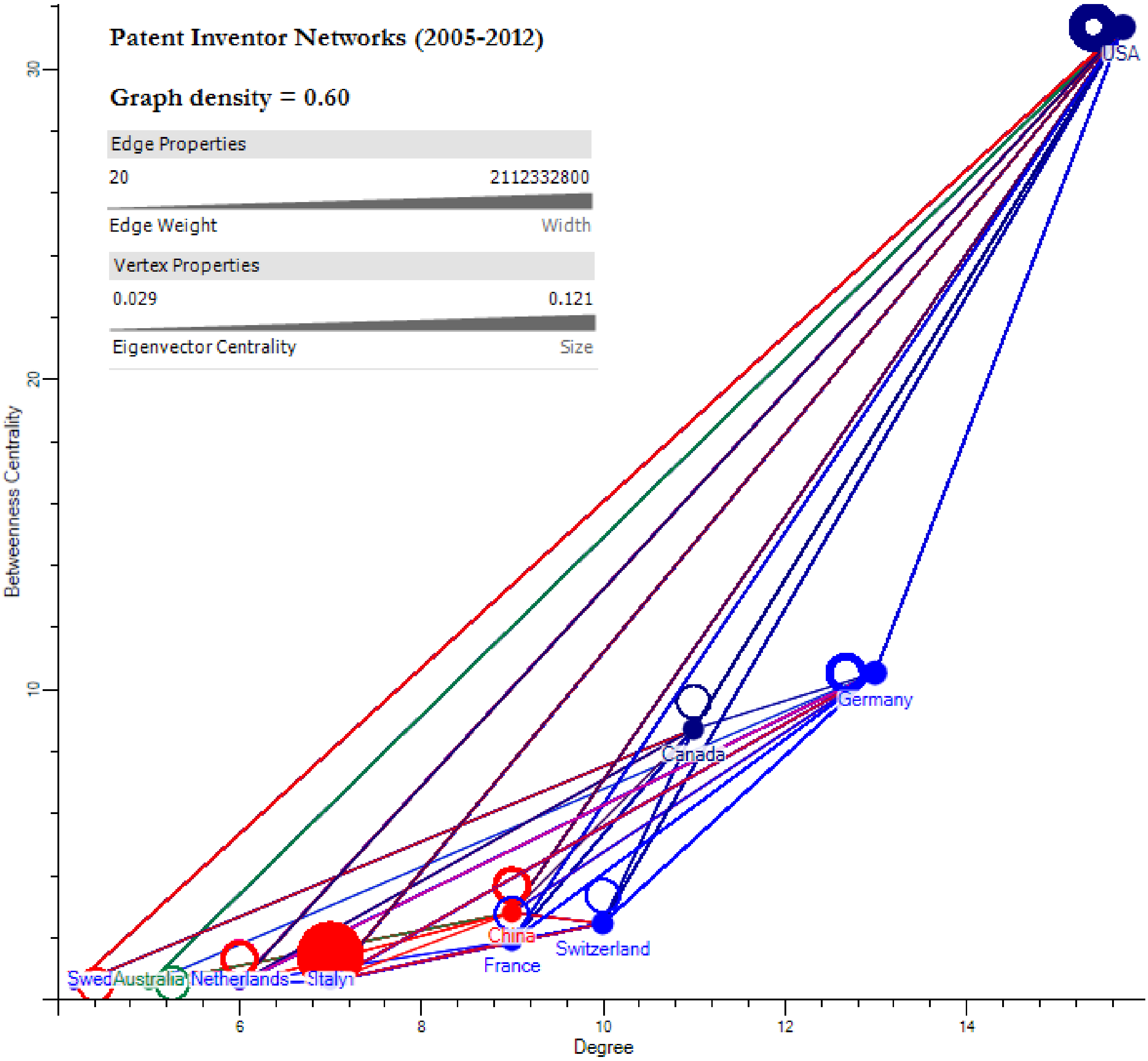
Figure 4. Co-Inventors: International research collaborations in different time periods

Figure 4A: Co-Inventor research collaborations (1990-2004)



Source: Author's derivation from solar PV co-inventor networks from PATSTAT database.

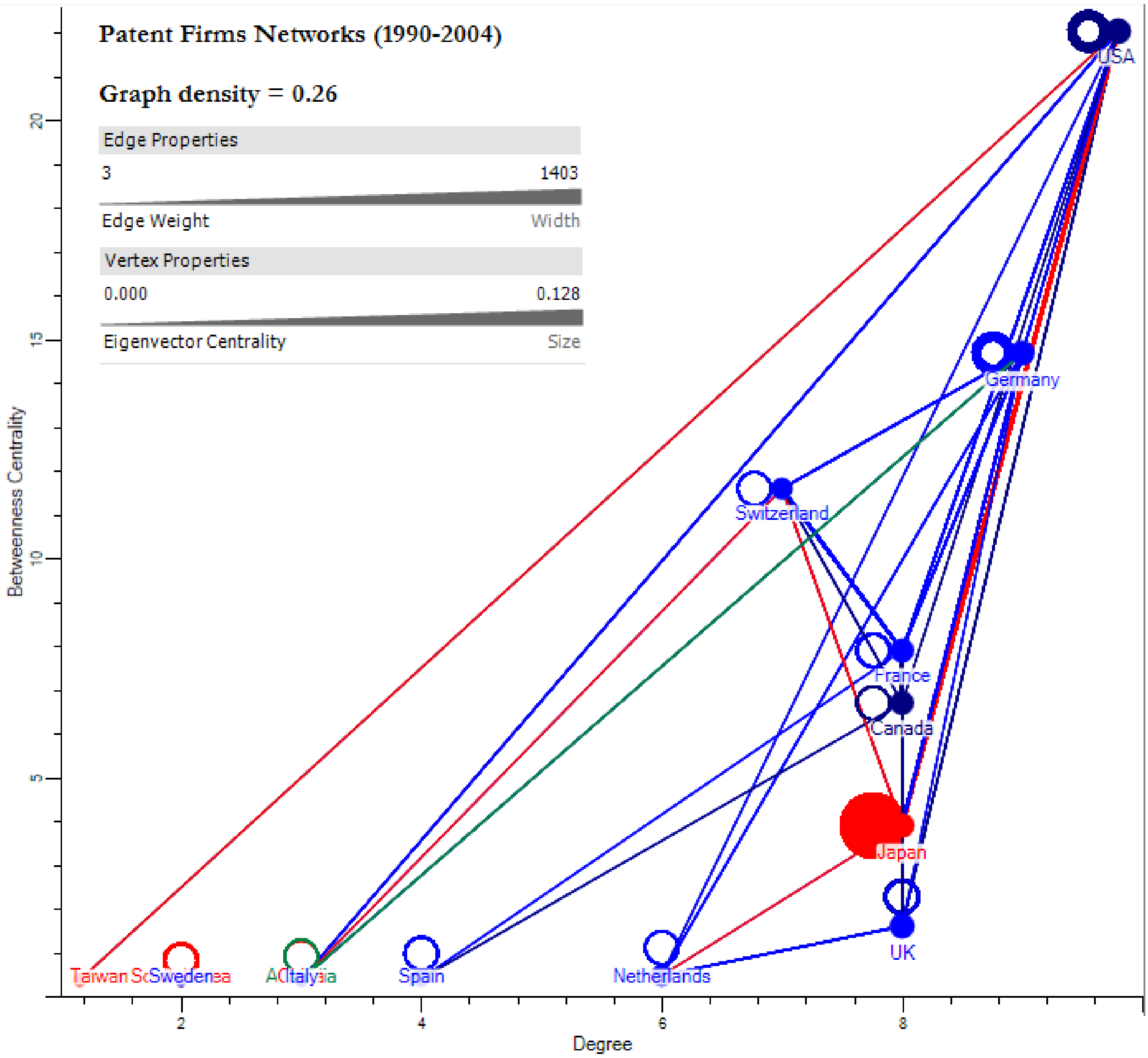
Figure 4B: Co-Inventor research collaborations (2005-2012)



Source: Author's derivation from solar PV co-inventor networks from PATSTAT database.

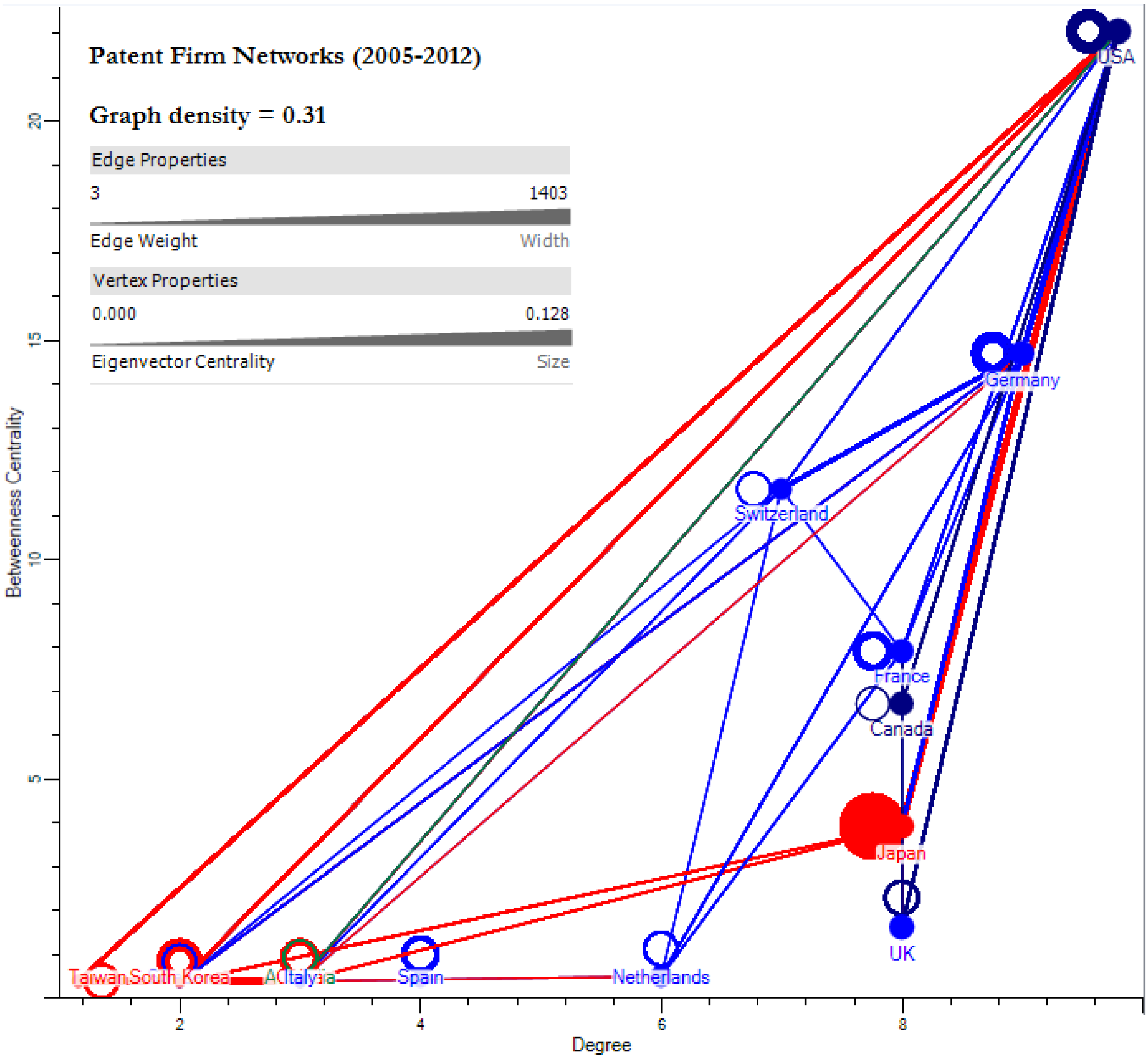
Figure 5. Inter-Firm research collaborations: International pairs in different time periods

Figure 5A: Inter-Firm research collaborations (1990-2004)



Source: Author's derivation from solar PV partner firm networks from PATSTAT database.

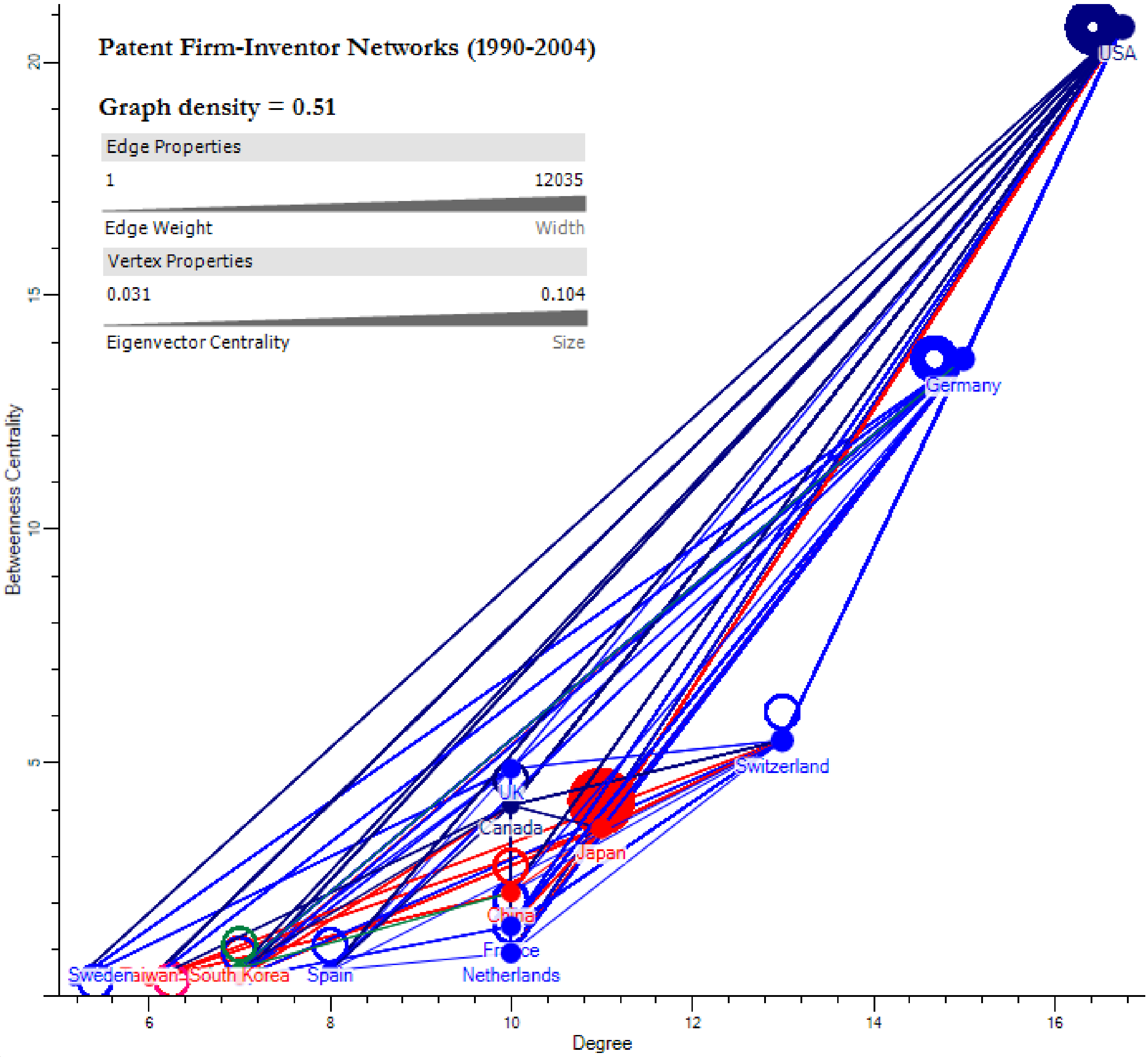
Figure 5B: Inter-Firm research collaborations (2005-2012)



Source: Author's derivation from solar PV partner firm networks from PATSTAT database.

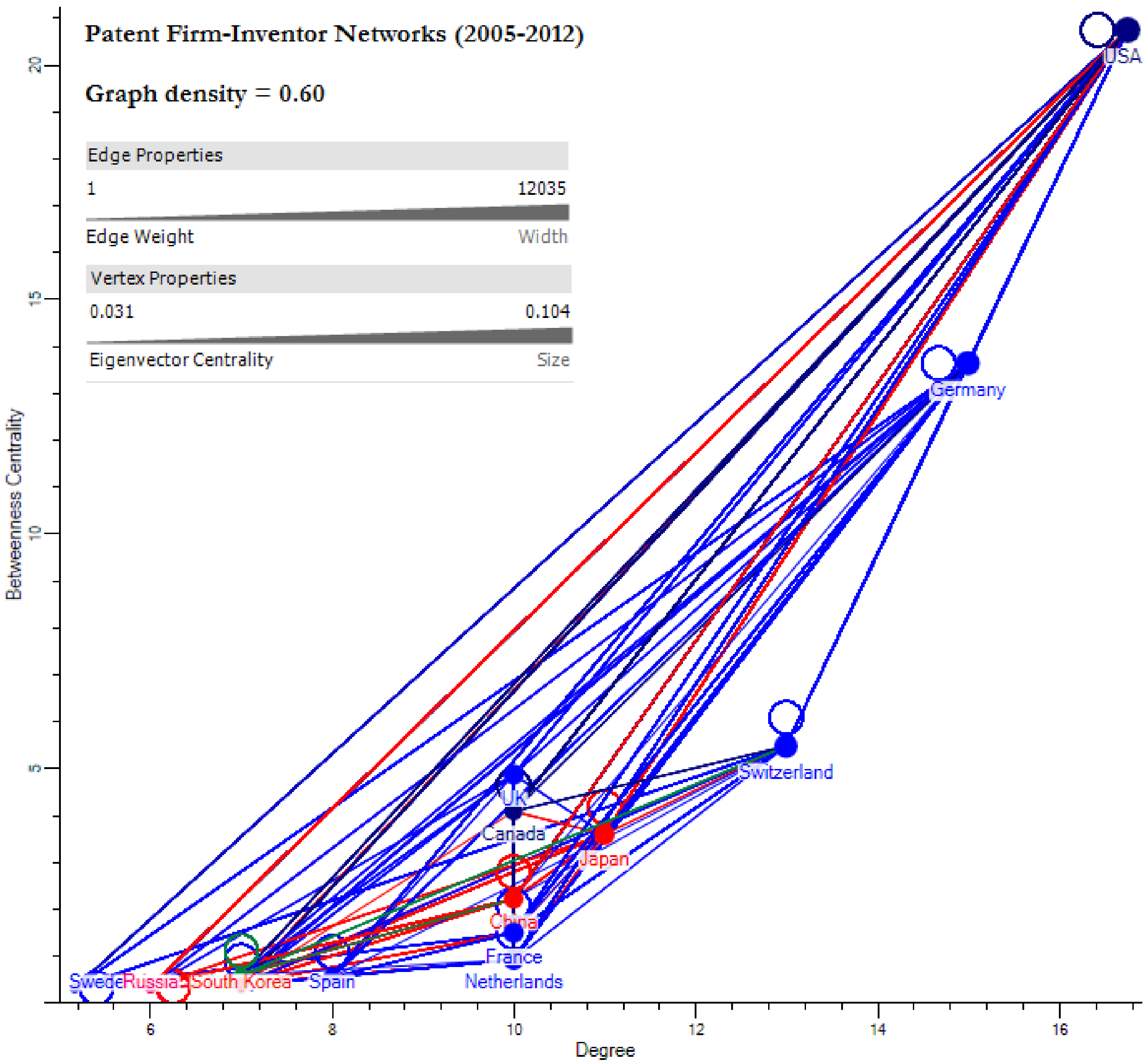
Figure 6. Firms' and Inventors' international research collaborations in two different time periods

Figure 6A: Firm-Inventor research collaborations (1990-2004)



Source: Author's derivation from solar PV firm-inventor networks from PATSTAT database.

Figure 6B: Firm-Inventor research collaborations (2005-2012)



Source: Author's derivation from solar PV firm-inventor networks from PATSTAT database.

4.4 Country profiles: who do countries collaborate with?

4.4.1 First-mover countries

Another way to analyse countries' access to knowledge spillovers is by considering who they undertake research collaborations with. EEG argues that although the research actors within a country are interested in tapping into global innovation networks, the research collaborations themselves tend to be with countries that are 'proximate' –in terms of spatial distance and/or having institutional similarities (Asheim et al., 2007; Storper & Venables, 2004). Furthermore, EEG demonstrates that if countries collaborate in one time period, they are more likely to collaborate with the same countries again in future time periods (Heimeriks & Boschma, 2013). This does not mean that these countries are unlikely to collaborate with others as well – it just means that original partners tend to maintain a favoured status over time, demonstrating a path dependency in research collaborations between countries.

In order to provide a balanced assessment of the relevance of partner countries within each country profile, a ratio of observed/expected partnerships is used (represented in the blue bar graphs below). This is in contrast to the actual percentage that partner countries account for in the different datasets (represented by the red dashes). The observed/expected ratio is derived from Luukkonen et al.'s (1992) study of international research collaborations and country preferences. It recognises that certain countries, such as the USA, have a large number of publications and a larger tendency to collaborate with other countries. Therefore, using the actual percentage of publications would overstate the importance of the USA in collaborations with each country. The observed/expected ratio instead creates a standardised index calculation where the observed number is compared with the expected number of research collaborations of the country, given the size and tendency of each country to collaborate. The calculation for the observed/expected ratio is given below.

$$\text{Observed/ expected ratio} = \frac{C_{xy} * T}{C_x * C_y}$$

C_{xy} = number of collaborations between country x and y in the time period

T = total number of collaborations of all the countries in the dataset in that time period

C_x = total number of collaborations for country x

C_y = total number of collaborations for country y

Luukkonen et al. (1992, p. 107) note that, "when the index value exceeds one, there are more collaborations between a pair of countries than expected, given their size and tendency to collaborate[...]". Therefore, this index is very useful in providing a balanced ranking of countries' tendencies to collaborate with others – enabling a ranking profile of different countries' relevance in research collaborations. The following sub-sections will analyse the collaboration between selected first-mover countries, starting first with Japan and Germany. It will then review the collaborations of the most central late-comer country, China. It will then end with the USA, which has demonstrated in the previous section its centrality and tendency to collaborate with all other countries in the network. Therefore the last section will reveal the most important relationships for the most central country in solar PV research – indicating these countries' probability of obtaining high-value knowledge spillovers that would potentially not have been accessed through its own connections.

4.4.2 First-mover countries: Japan and Germany

In analysing the observed/expected ratios of both Japan and Germany in both time periods shows that spatial proximity continues to matter over time and in both research publications and patents. Japan's most important partners that exceed the observed/expected ratio of 1 are South Korea and Australia for scientific research publications. For Germany, the most relevant countries that exceed the value of 1 are its European neighbours, including Russia.

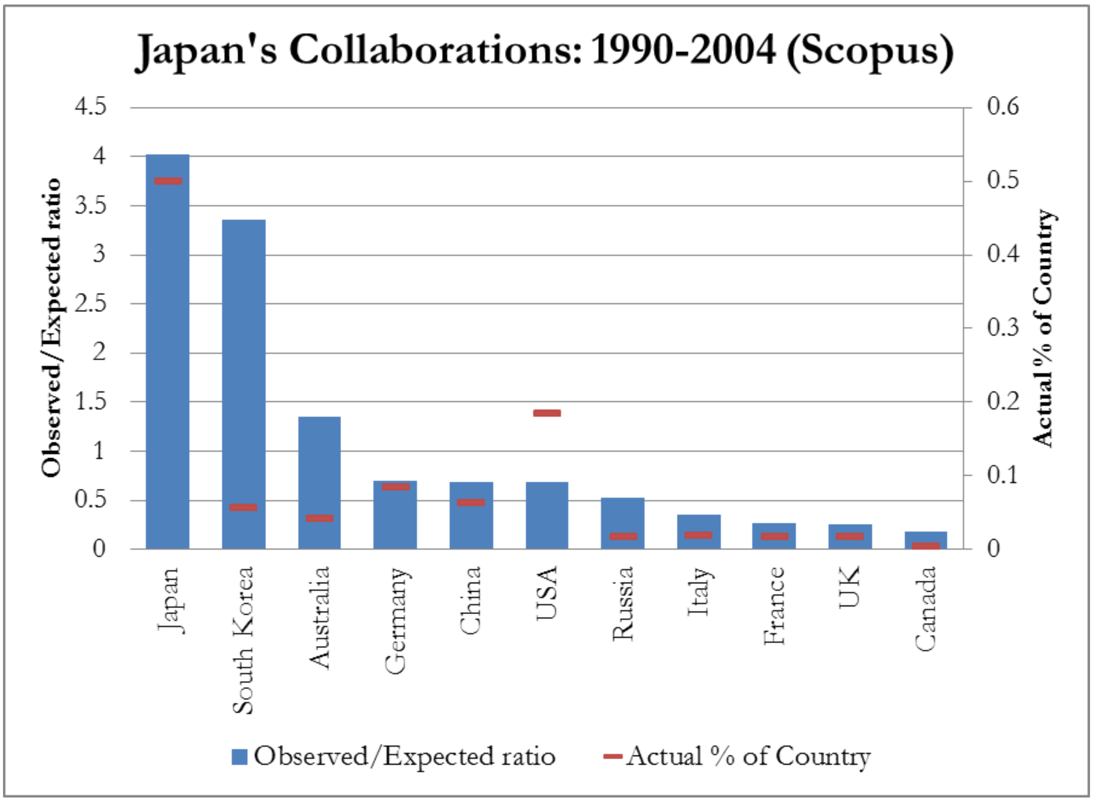
Whilst the "neighbour effect" largely persists for Germany's collaborations across all datasets, there is a difference for Japan between research collaborations and patents. For scientific research, Japan also tends to undertake collaborations with its neighbours including China. However for international collaborations in patents, its foremost partners are the

USA, Switzerland, or Canada (depending on the patent dataset and time period). At face value, this finding is surprising. Studies that compare research collaborations between the global scientific community and industry demonstrate that the latter requires more spatial proximity between collaborators in order to limit the geographical spillovers of proprietary research efforts (Kwon et al., 2011; Ponds et al., 2007). However, one of the limitations of patent datasets is that it does not list all the different actors within a firm that participate in patent collaborations. This is why this research does include intra-country collaborations, which demonstrate the continued importance of collaborations at the national level. In fact all the observation/expected ratios of intra-country collaborations are higher than 1, representing the clustering of research activities at the national level.

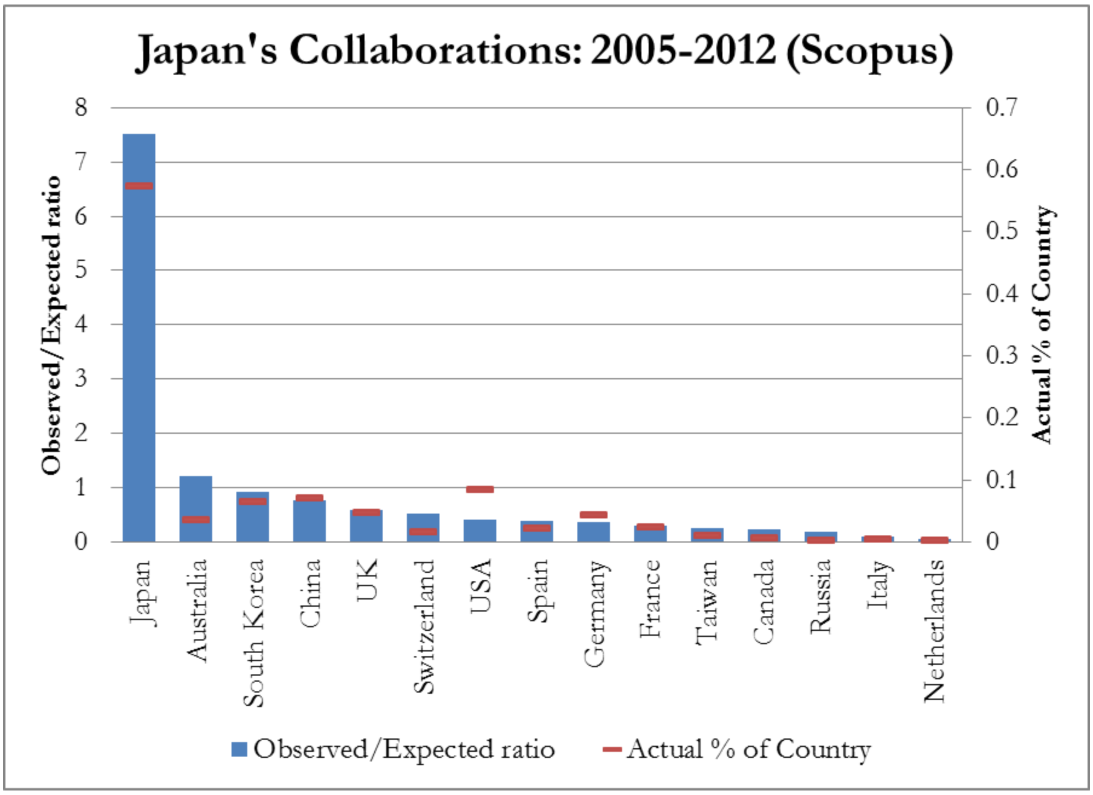
It is also very interesting to note the relevance of Australia and Switzerland for both Japan and Germany. Whilst it can be argued that Australia's relative proximity to Japan and Switzerland's proximity to Germany facilitates collaboration between neighbours, it is not as obvious that Australia should figure so prominently for Germany, and Switzerland for Japan. However these findings align with the 'centrality' measures of these countries, as discussed in the previous section, where Australia plays a central role in research publications, and Switzerland plays a more central role in patent collaborations. What is also interesting to note is China's position within Japan's and Germany's country profiles. Whilst it features as a prominent research partner in scientific collaborations with Japan and Germany, it has a much lower country ranking in patent networks for these countries.

Figure 7. Japan's profiles of country partners in two time periods

Figure 7A. Scopus research collaborations with Japanese authors in two time periods

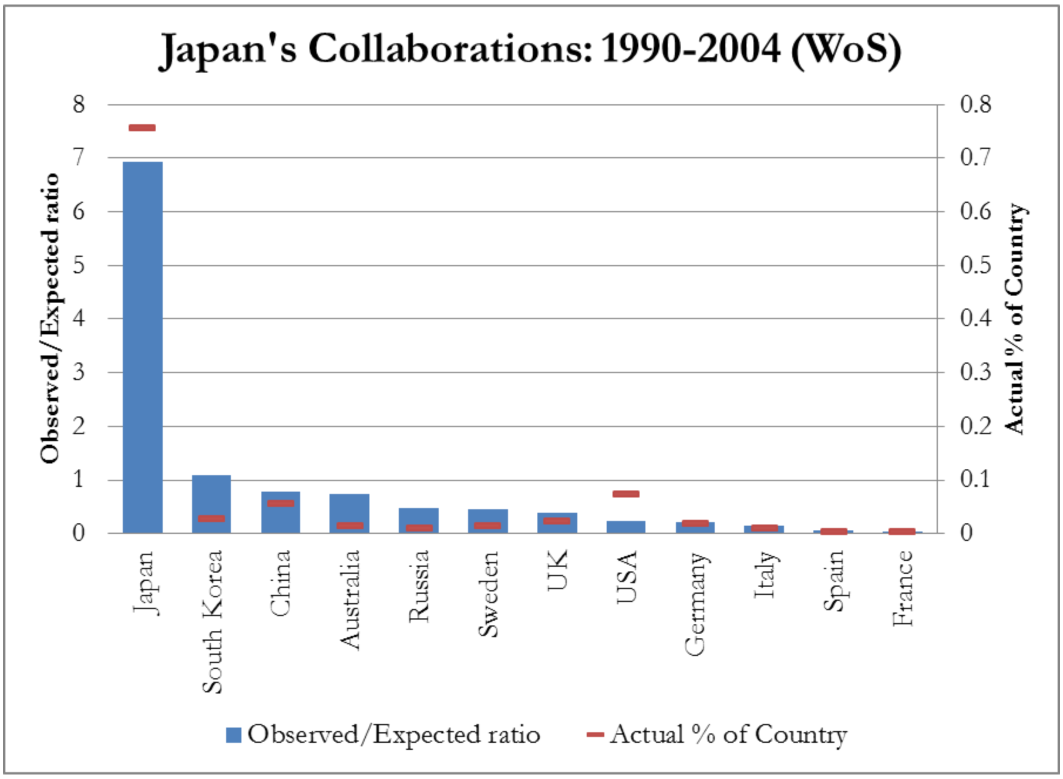


Source: Author's calculations from publications downloaded from Scopus database.

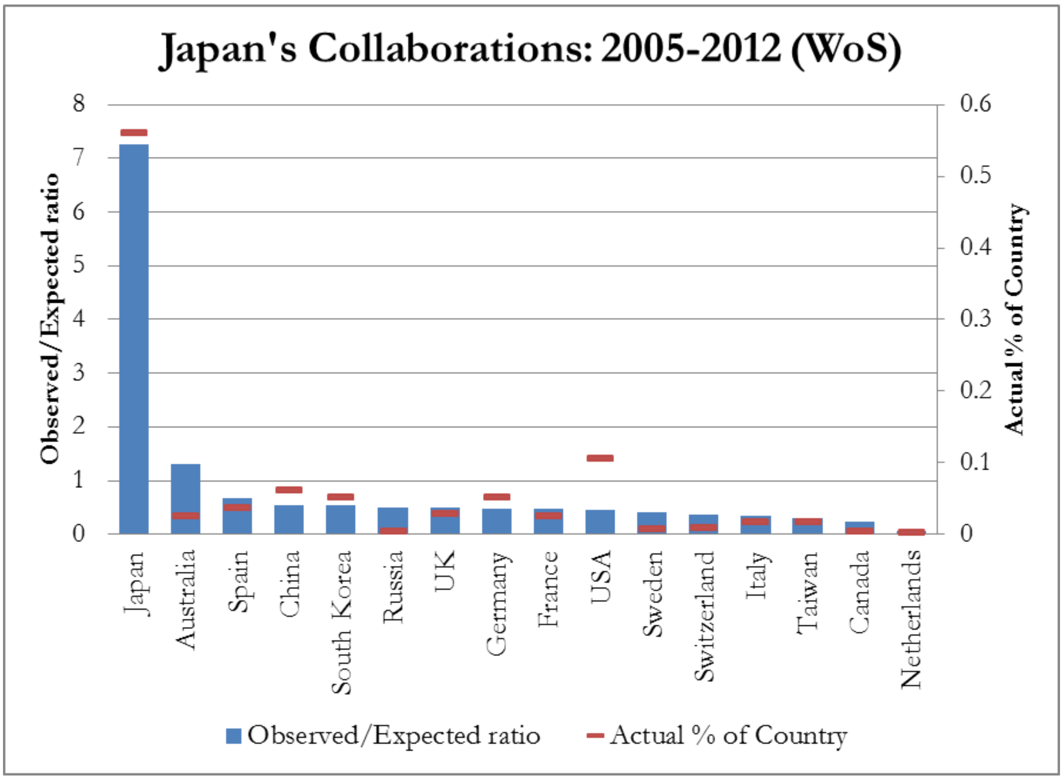


Source: Author's calculations from publications downloaded from Scopus database.

Figure 7B. Web of Science research collaborations with Japanese institutions in two time periods

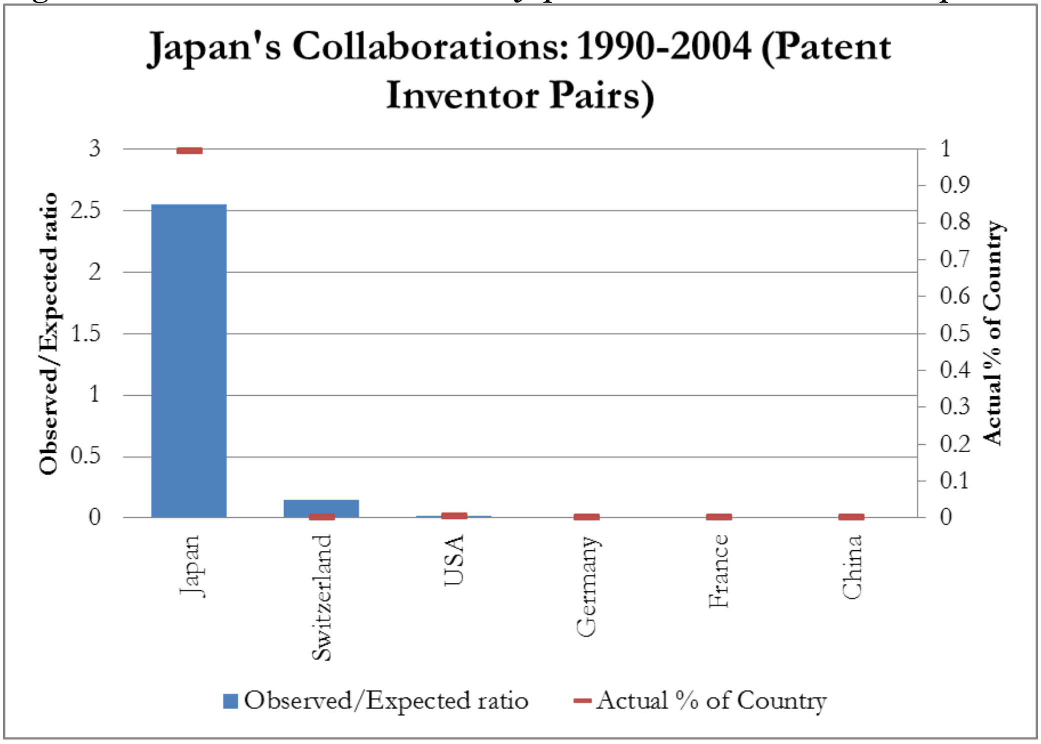


Source: Author's calculations from publications downloaded from Web of Science database.

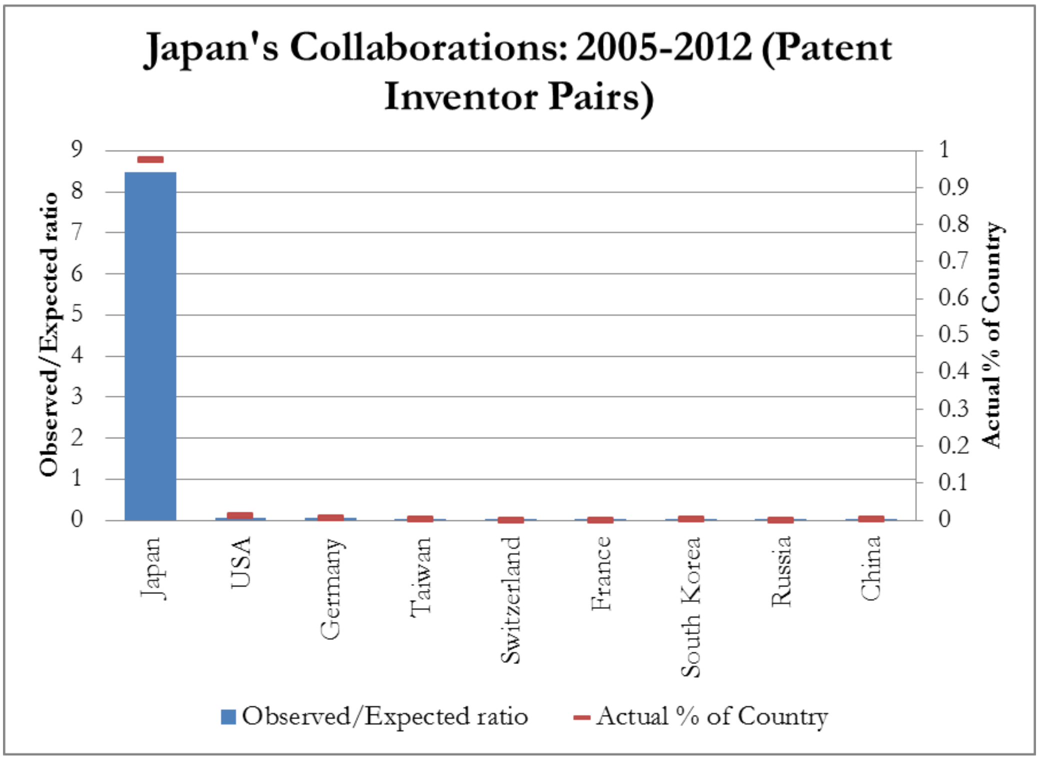


Source: Author's calculations from publications downloaded from Web of Science database.

Figure 7C. Patent collaborations with Japanese inventors in two time periods

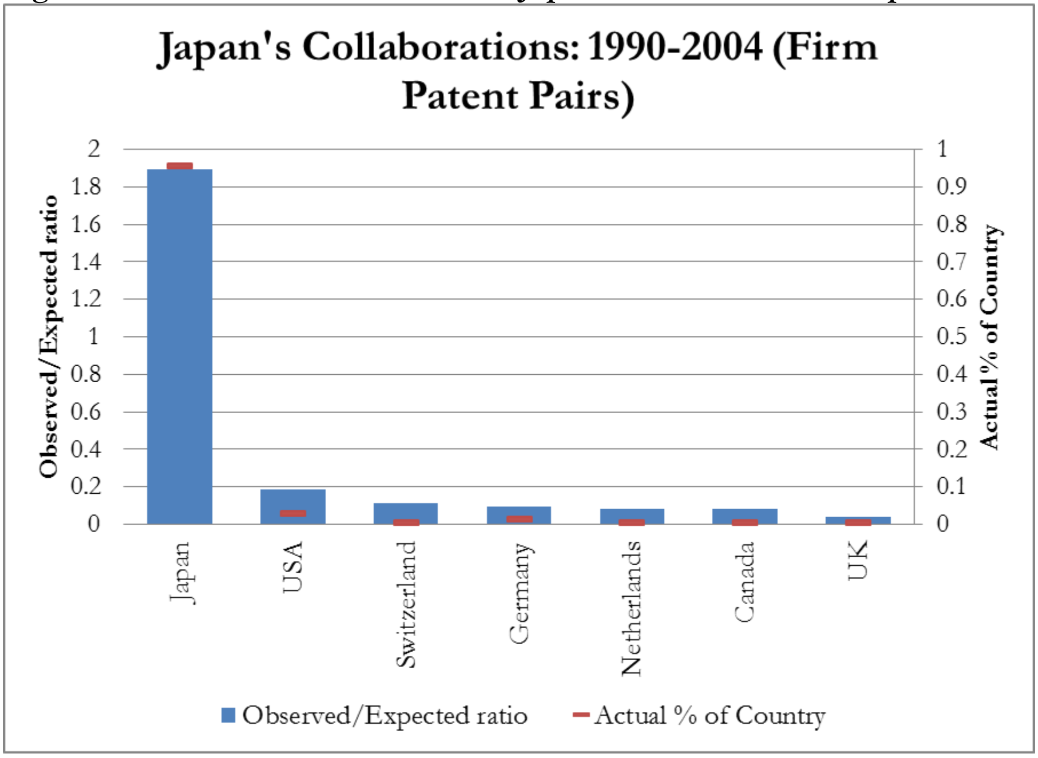


Source: Author's calculations from patents downloaded from PATSTAT database.

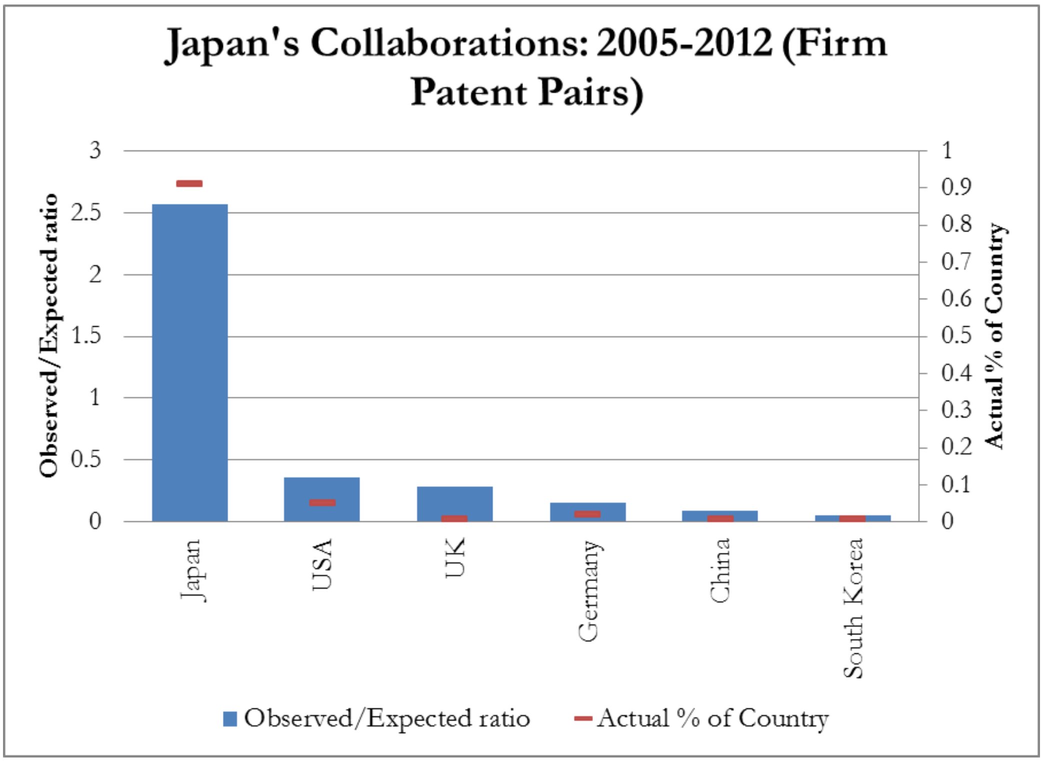


Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 7D. Patent collaborations with Japanese firms in two time periods

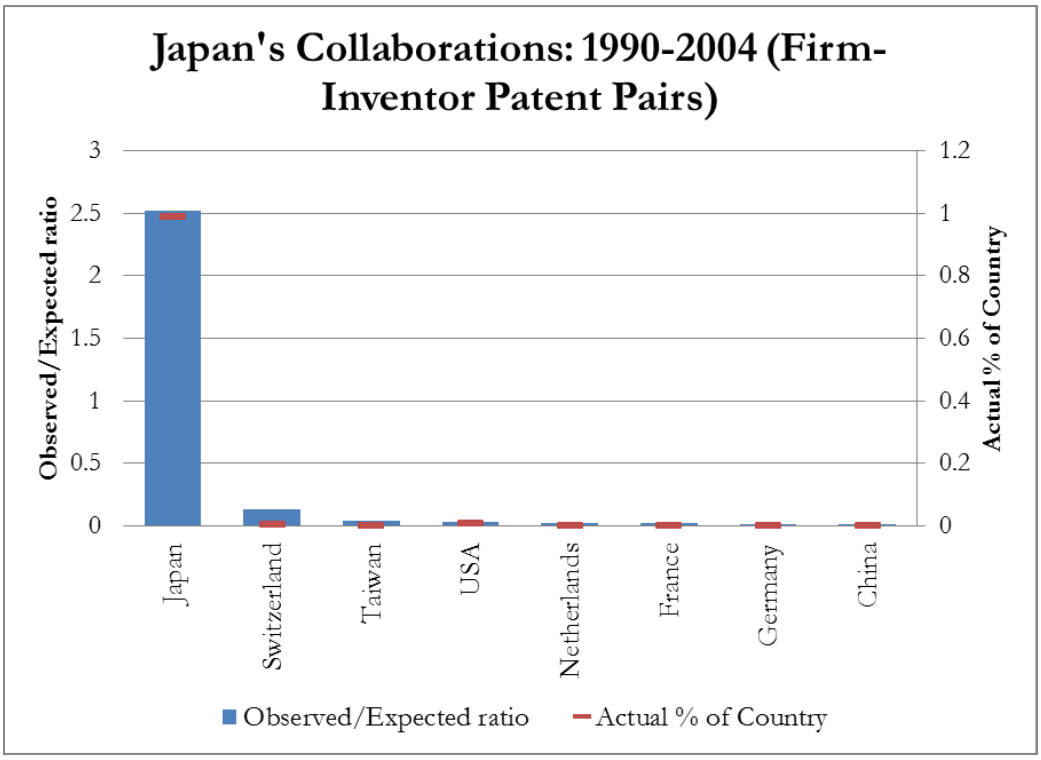


Source: Author's calculations from patents downloaded from PATSTAT database.

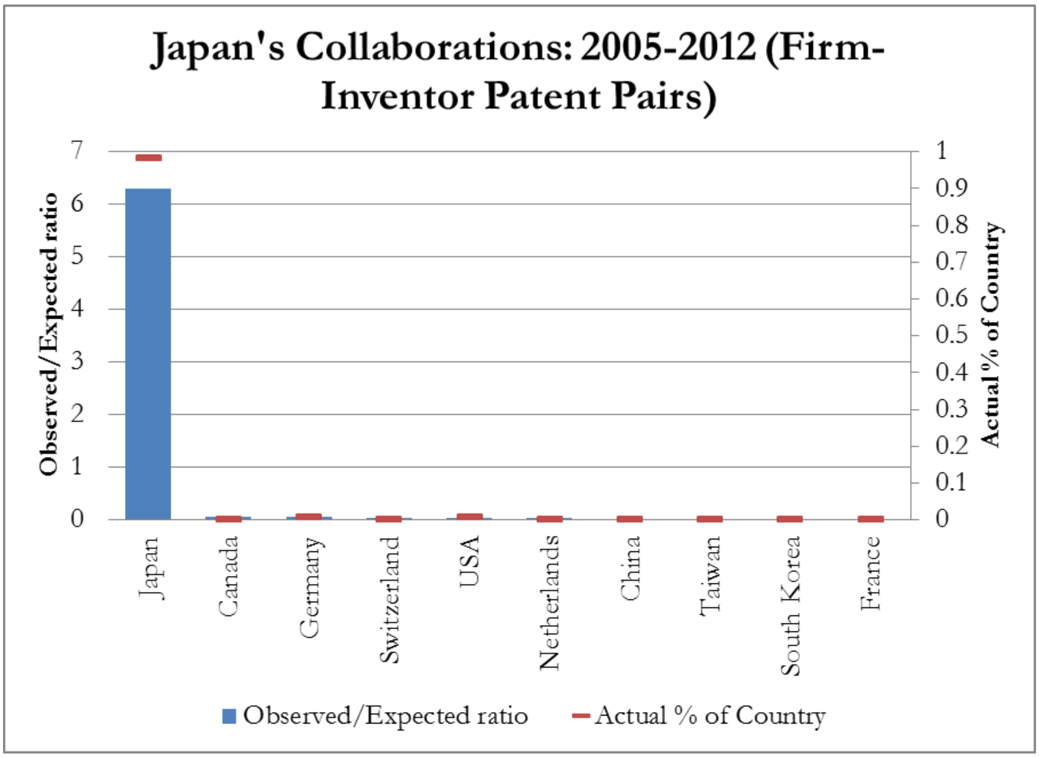


Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 7E. Patent collaborations between Japanese firms and domestic/foreign inventors in two time periods



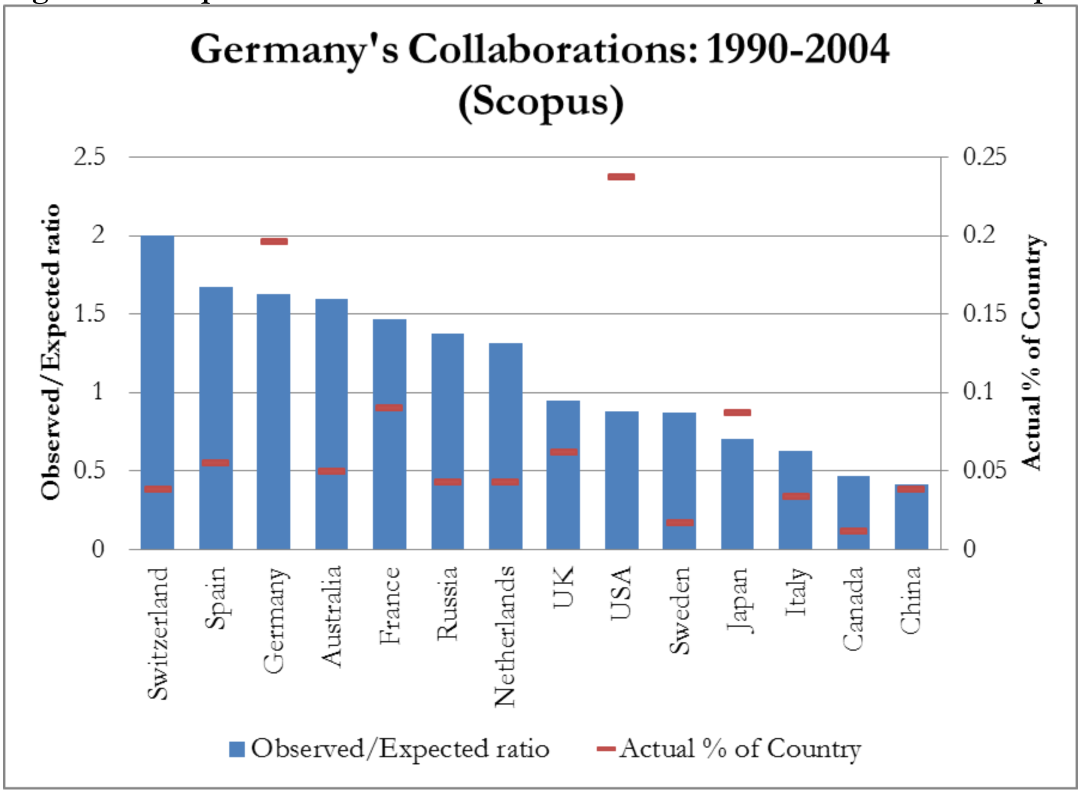
Source: Author's calculations from patents downloaded from PATSTAT database.



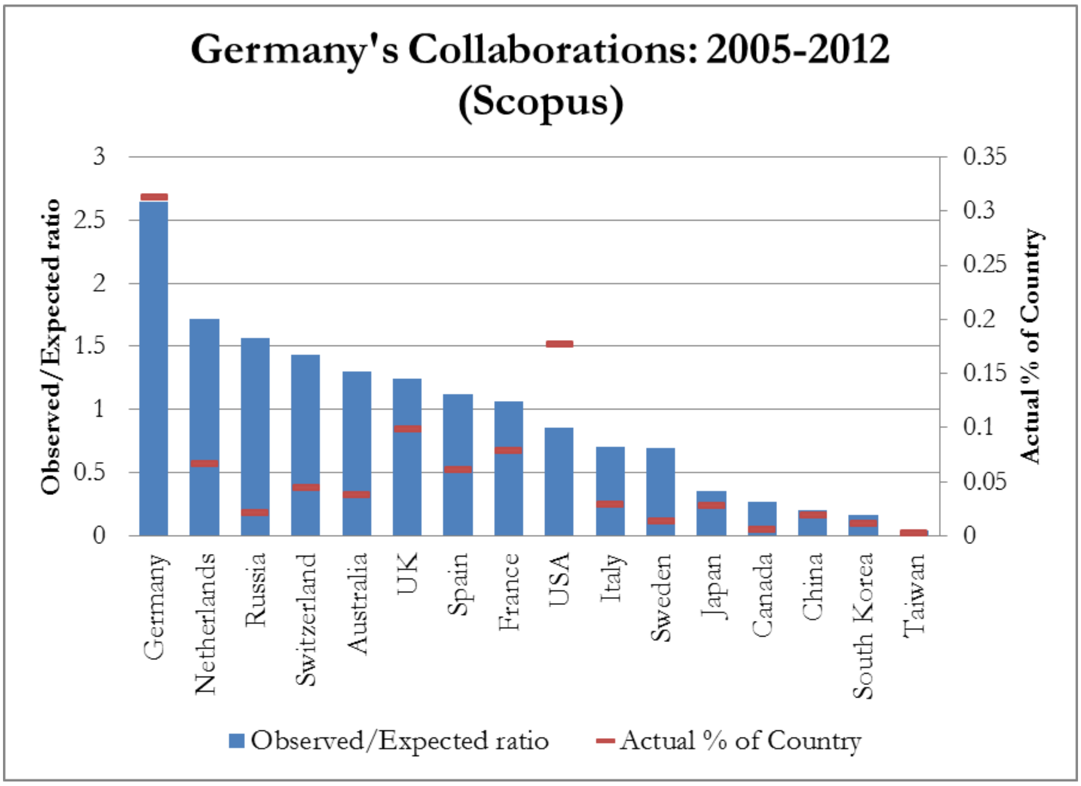
Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 8.Germany's profiles of country partners in two time periods

Figure 8A. Scopus research collaborations with German authors in two time periods

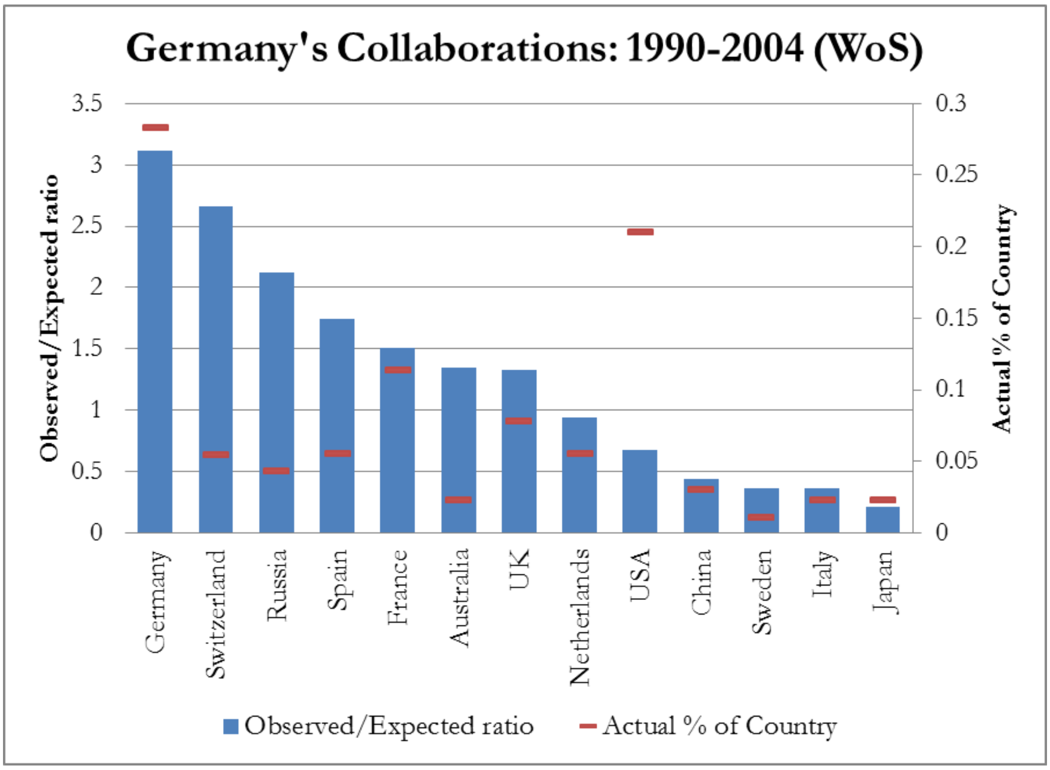


Source: Author's calculations from research publications downloaded from Scopus.

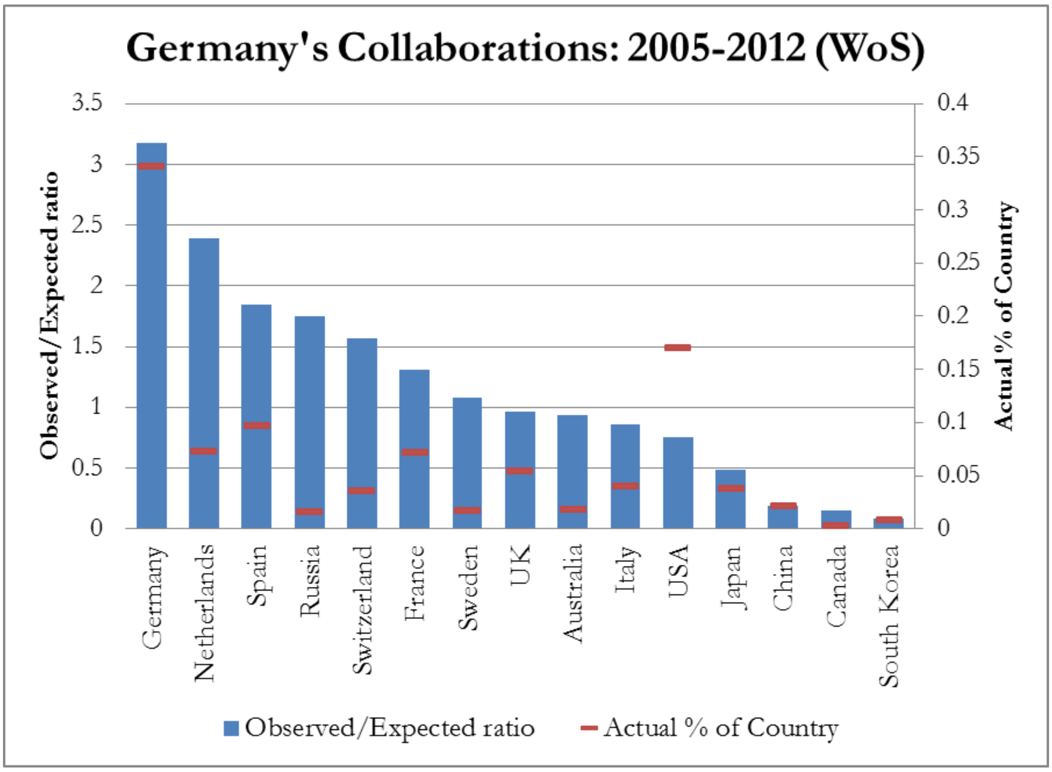


Source: Author's calculations from research publications downloaded from Scopus.

Figure 8B. Web of Science research collaborations with German institutions in two time periods

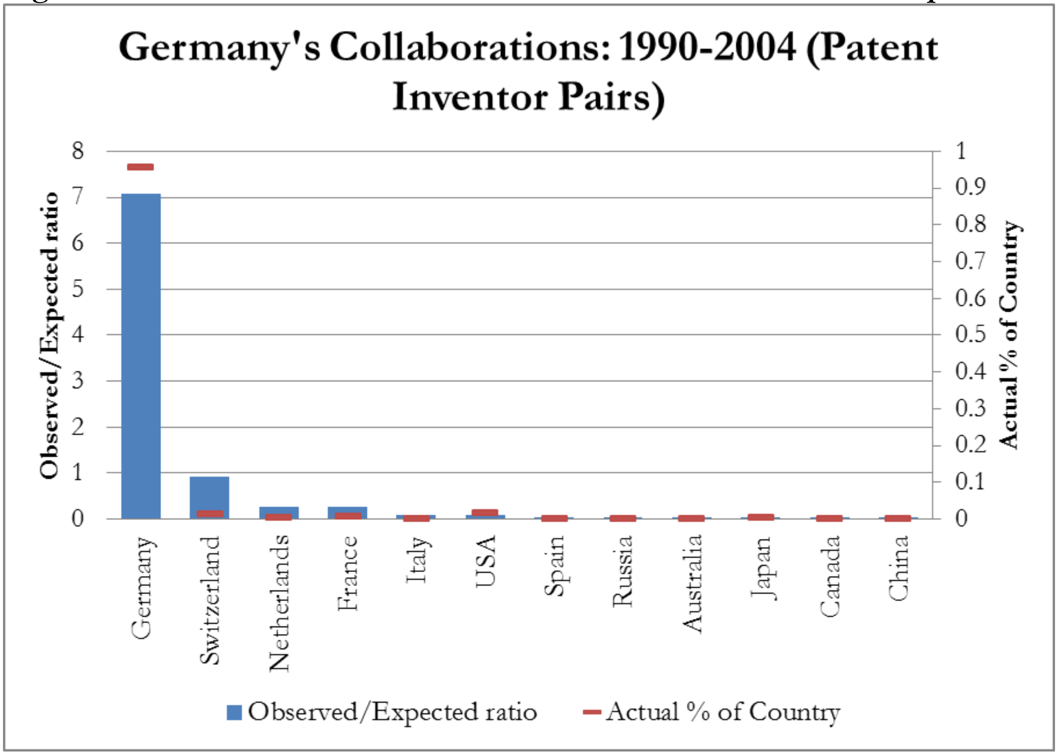


Source: Author's calculations from research publications downloaded from Web of Science.

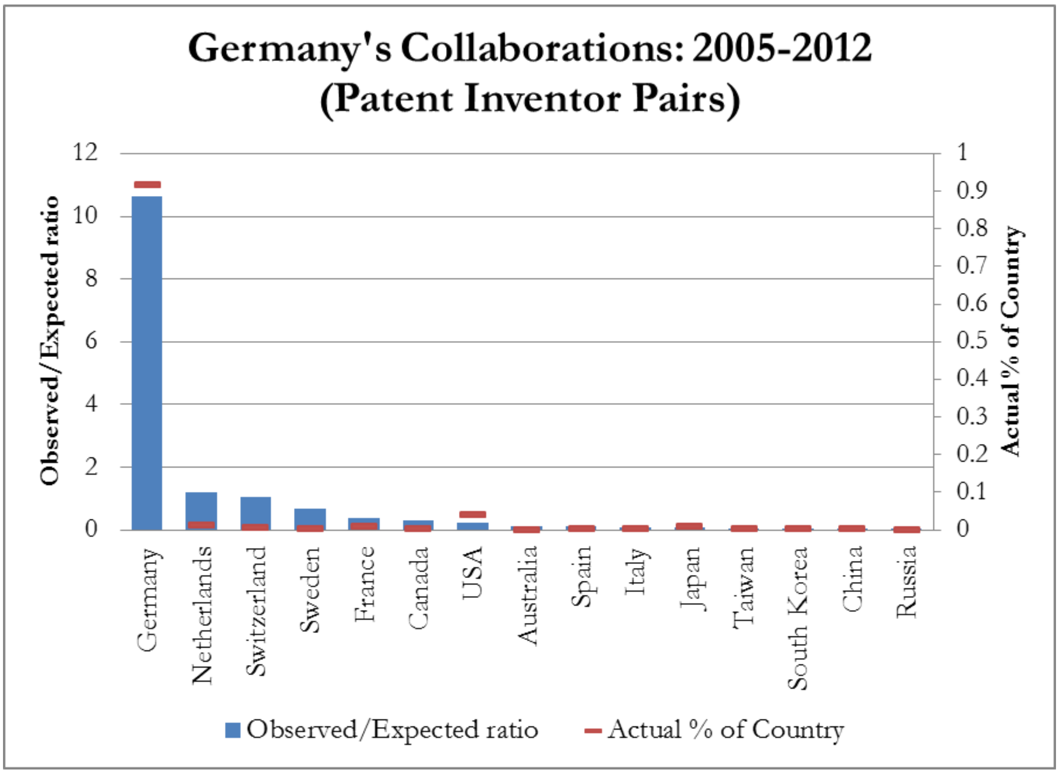


Source: Author's calculations from research publications downloaded from Web of Science.

Figure 8C. Patent collaborations with German inventors in two time periods

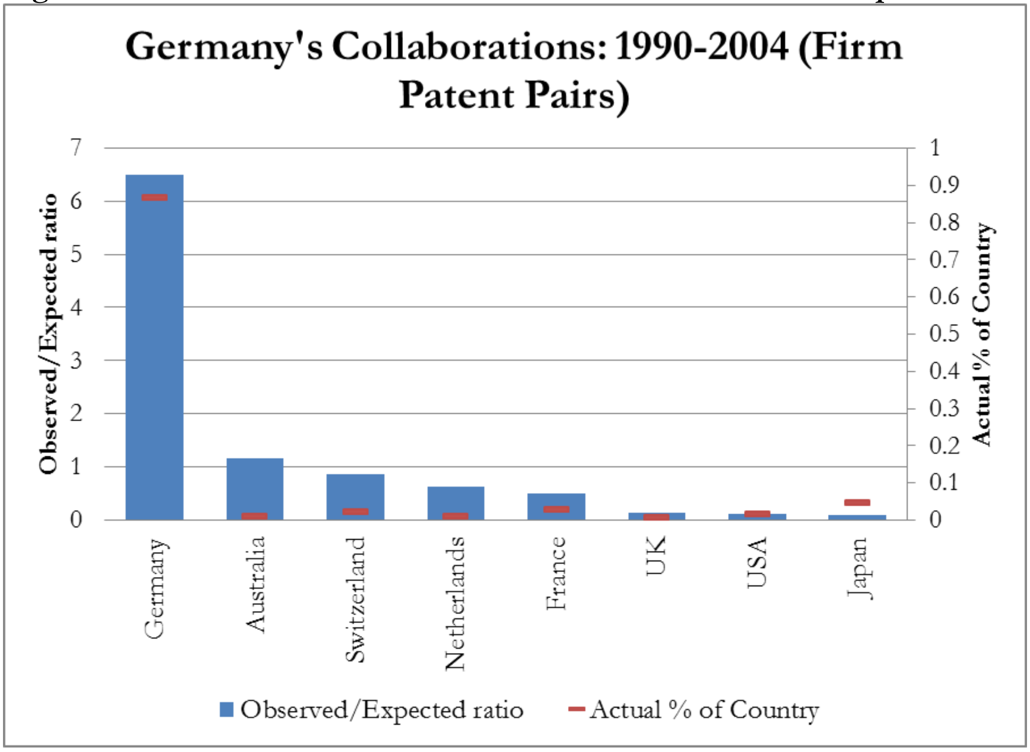


Source: Author's calculations from patents downloaded from PATSTAT database.

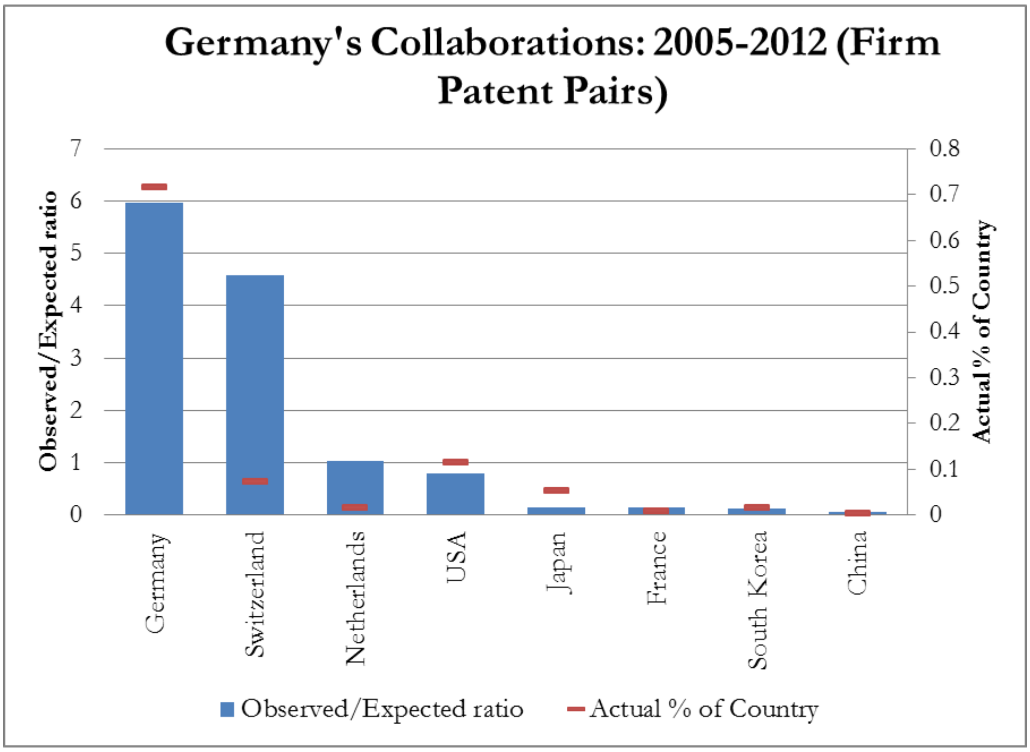


Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 8D. Patent collaborations with German firms in two time periods

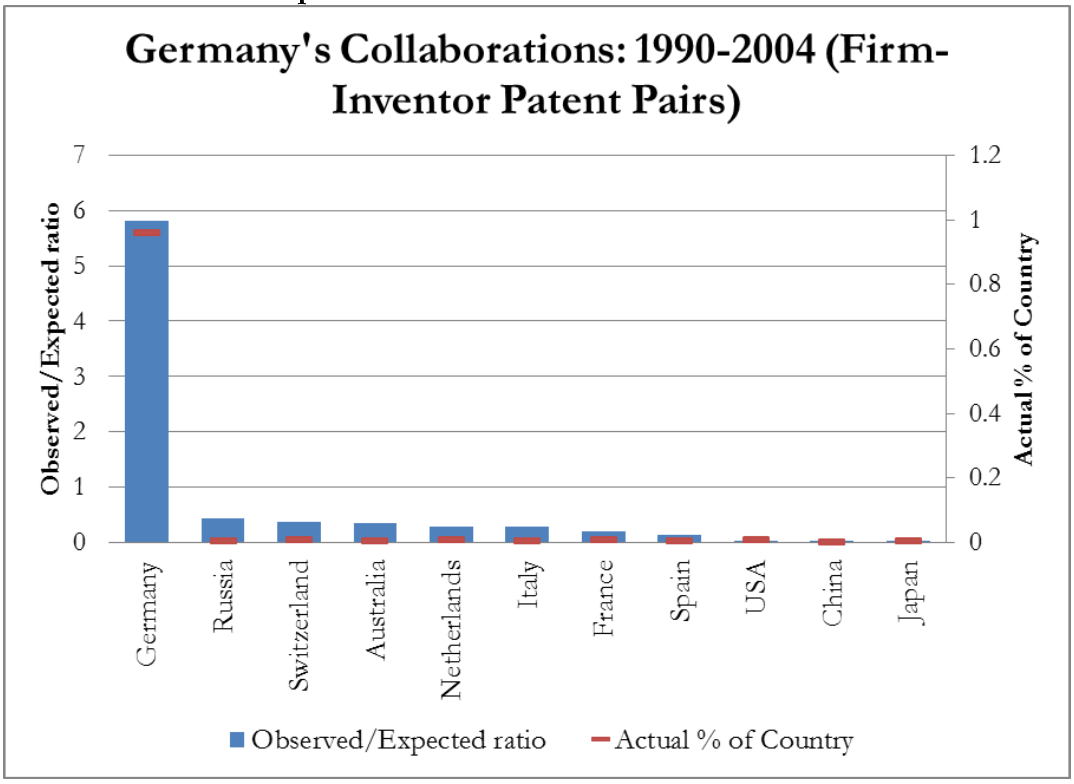


Source: Author's calculations from patents downloaded from PATSTAT database.

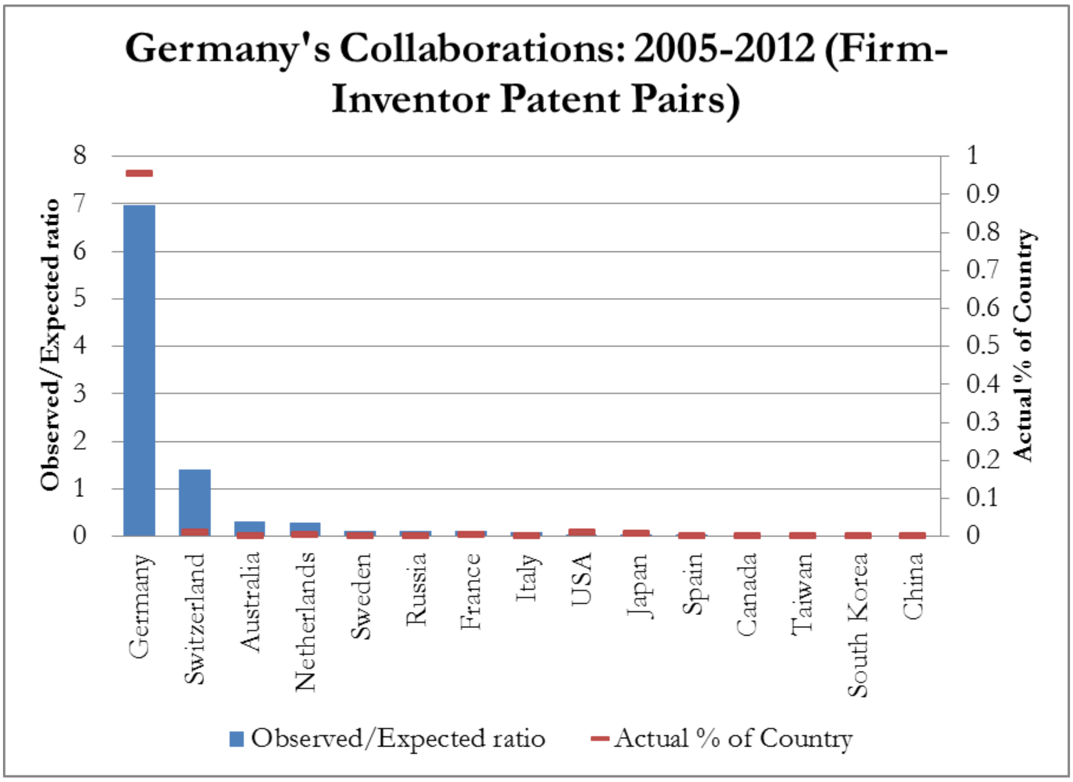


Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 8E. Patent collaborations between German firms and domestic/foreign inventors in two time periods



Source: Author's calculations from patents downloaded from PATSTAT database.



Source: Author's calculations from patents downloaded from PATSTAT database.

4.4.3 Late-comer economies: China

In examining the country partner profiles for China in each research dataset for both time periods, it is surprising that central first-mover countries do not have a higher ranking than countries such as Canada and Sweden (for research publications), and Australia (for patents). In *Scopus*, Canada has a value above 1 for the 1990-2004 period, while Sweden's value exceeds 1 in the 2005-2012 period. In WoS, both Canada and Sweden have values over 1 in the second time period. Though other first-mover countries such as the USA and Japan are amongst the top ranked countries for research collaborations, Germany is not as relevant a partner (especially in the second period from both *Scopus* and WoS datasets). One reason could be that China became less reliant on international collaborations in the second time period, as both the observed/expected ratios and the actual percentage of scientific research collaborations within China increased in the second time period.

Another interesting feature of China's relationships is the prominence of Australia in collaborating on patents. This is especially evident in the second time period in inter-firm partnerships and collaborations between firms and inventors. Australia's prominence in patent collaborations is surprising, given that Japan and the USA play a larger role in China's scientific research collaborations. One explanation could be the lack of industrial capacity in Australia. For Chinese firms, the importance of Australia in crystalline PV research can make it an attractive partner for undertaking research collaborations. For Australian firms and inventors, the lack of a large domestic industrial capacity hinders its ability to commercialise the potential technologies borne of patents. Collaborating with Chinese firms and inventors provides access to large industrial capacities that can enable the up-scaling of early stage technologies.

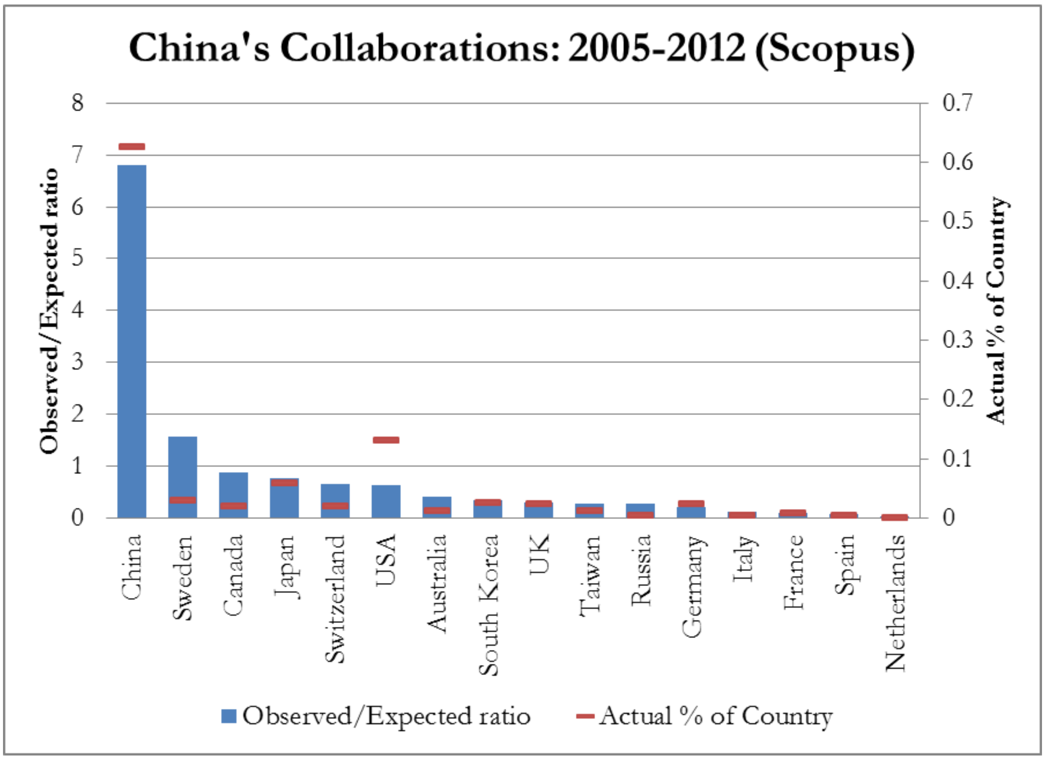
Therefore Canada and Sweden's relevance to China in scientific research publications, and Australia's prominence in industrial application, raises an additional hypothesis of considering the comparative sizes of industrial capacity in each partner country. Late-comer countries such as China would also be interested in collaborating with countries that have high technological capabilities in order to increase its own. Furthermore, it has the industrial capacity to attract countries with high technological capabilities but low existing industrial capacity (such as Australia, Canada and Sweden). Although this hypothesis is preliminary, it is corroborated by the research findings of relationships between Australia and China in

Chapter 5. It highlights how the absence of a domestic industry in first-mover countries can prompt industrial research collaborations with late-comer countries that seek to increase their own technological capabilities.

Figure 9. China's profiles of country partners in two time periods

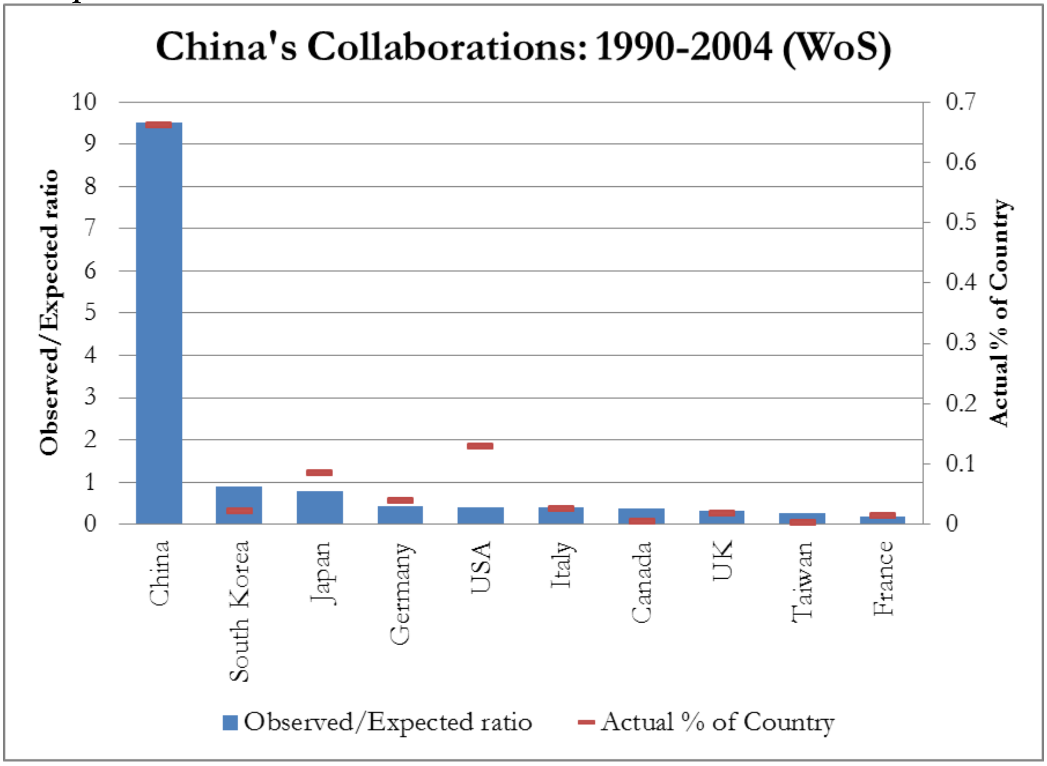
Figure 9A. Scopus research collaborations with Chinese authors in two time periods

Source: Author's calculations from research publications downloaded from Scopus.

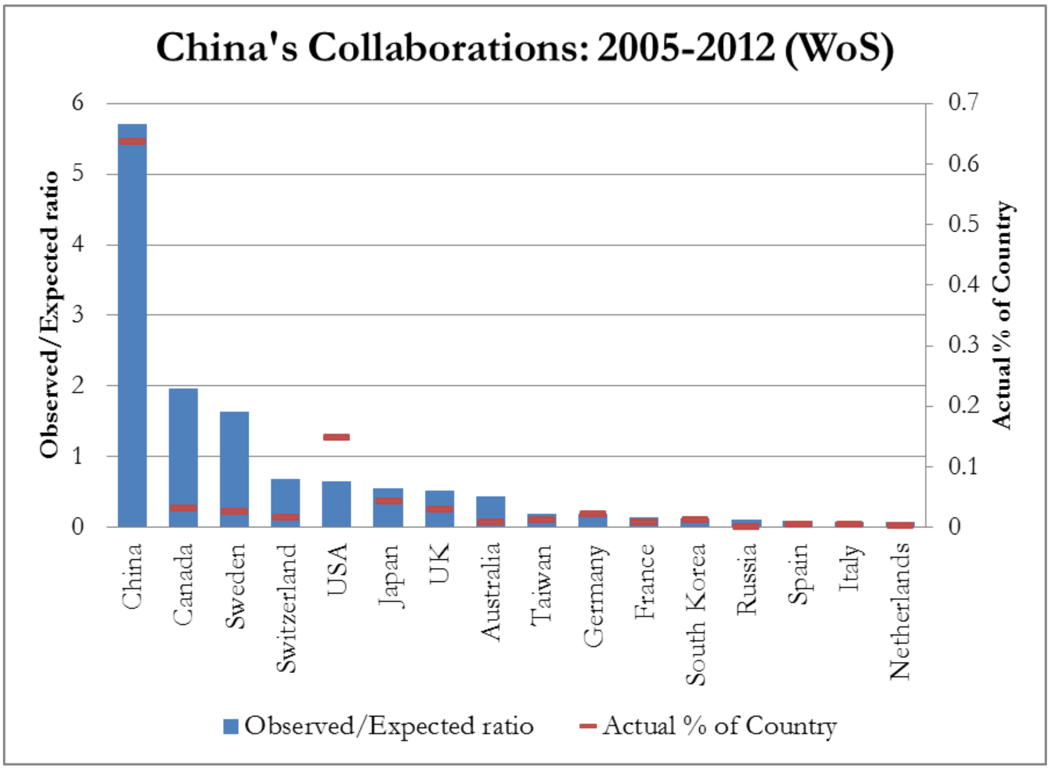


Source: Author's calculations from research publications downloaded from Scopus.

Figure 9B. Web of Science research collaborations with Chinese institutions in two time periods

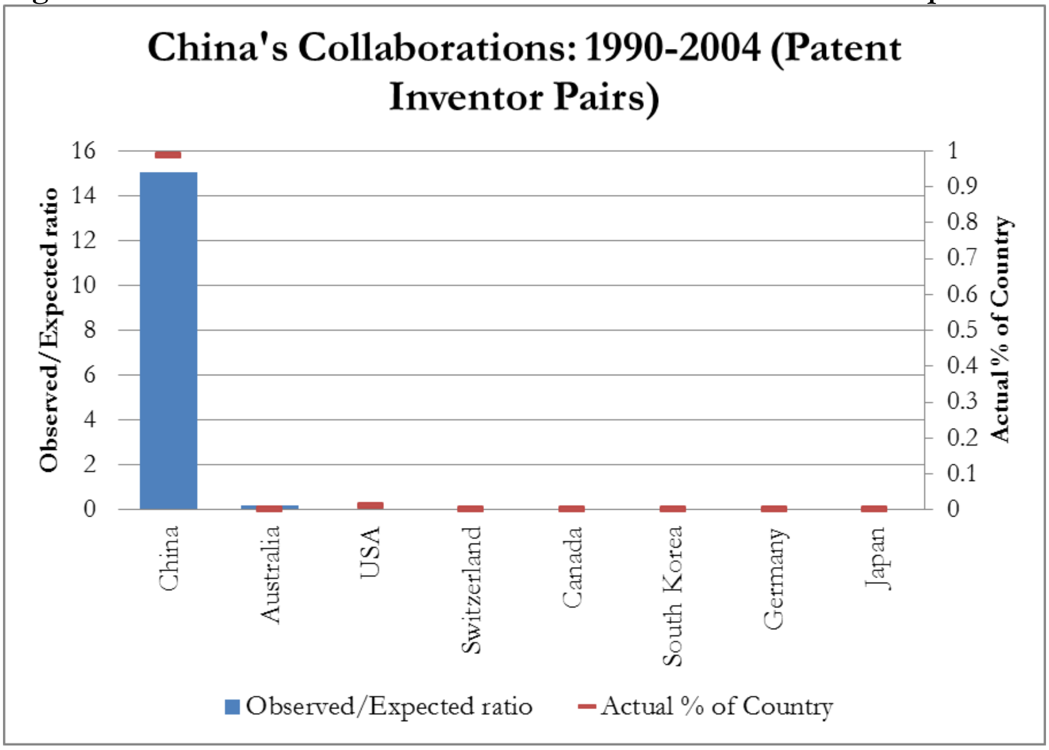


Source: Author's calculations from research publications downloaded from Web of Science.

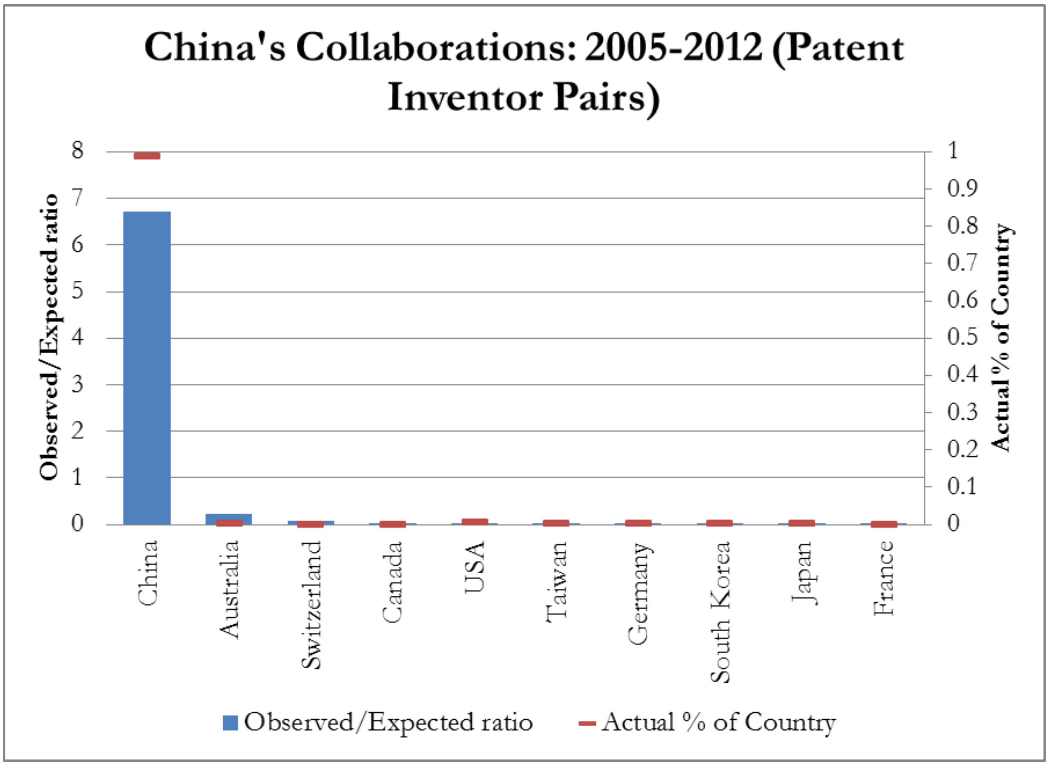


Source: Author's calculations from research publications downloaded from Web of Science.

Figure 9C. Patent collaborations with Chinese inventors in two time periods

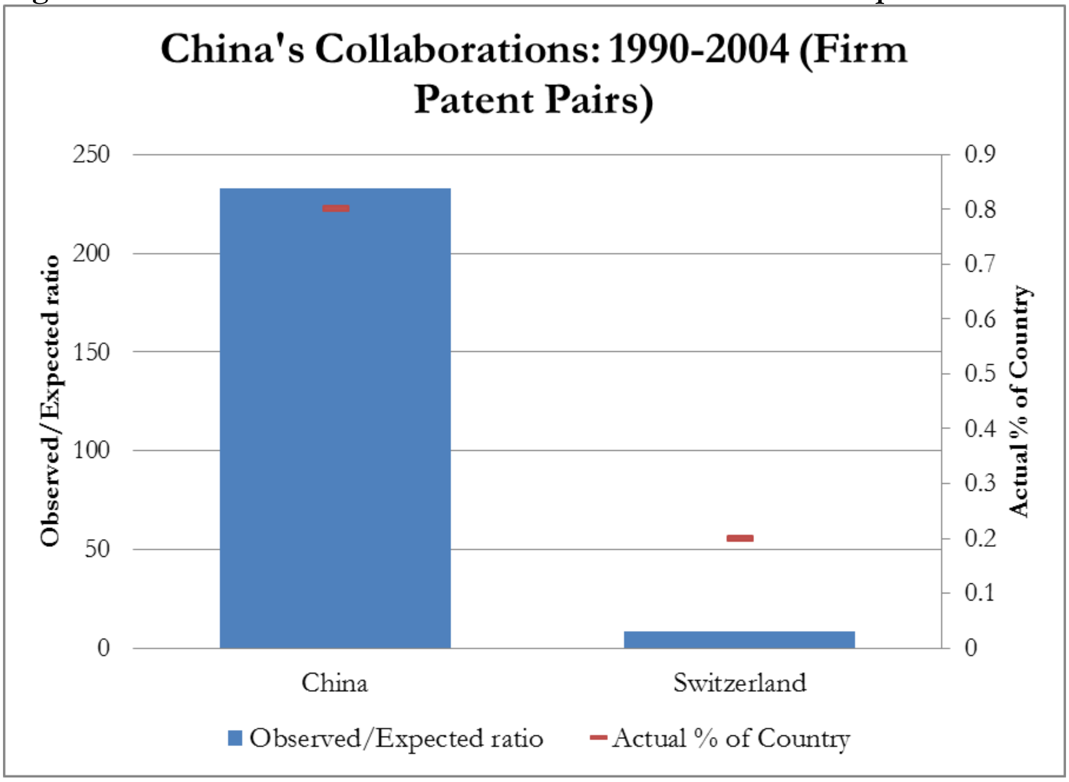


Source: Author's calculations from patents downloaded from PATSTAT database.

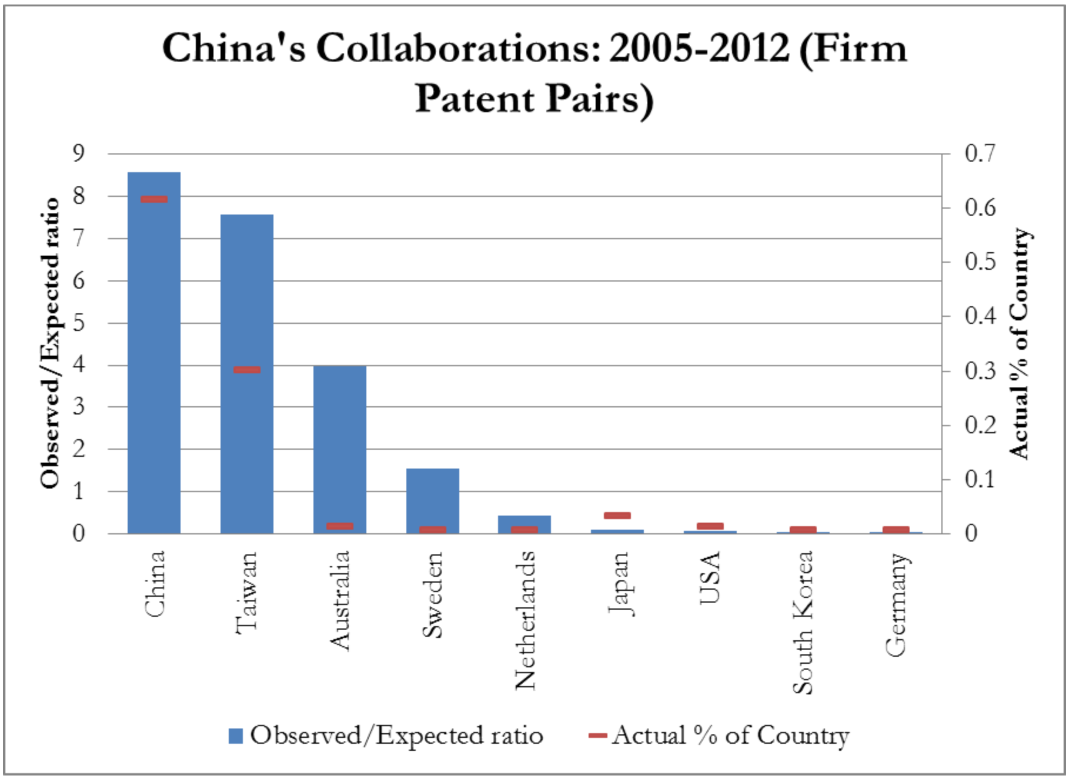


Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 9D. Patent collaborations with Chinese firms in two time periods



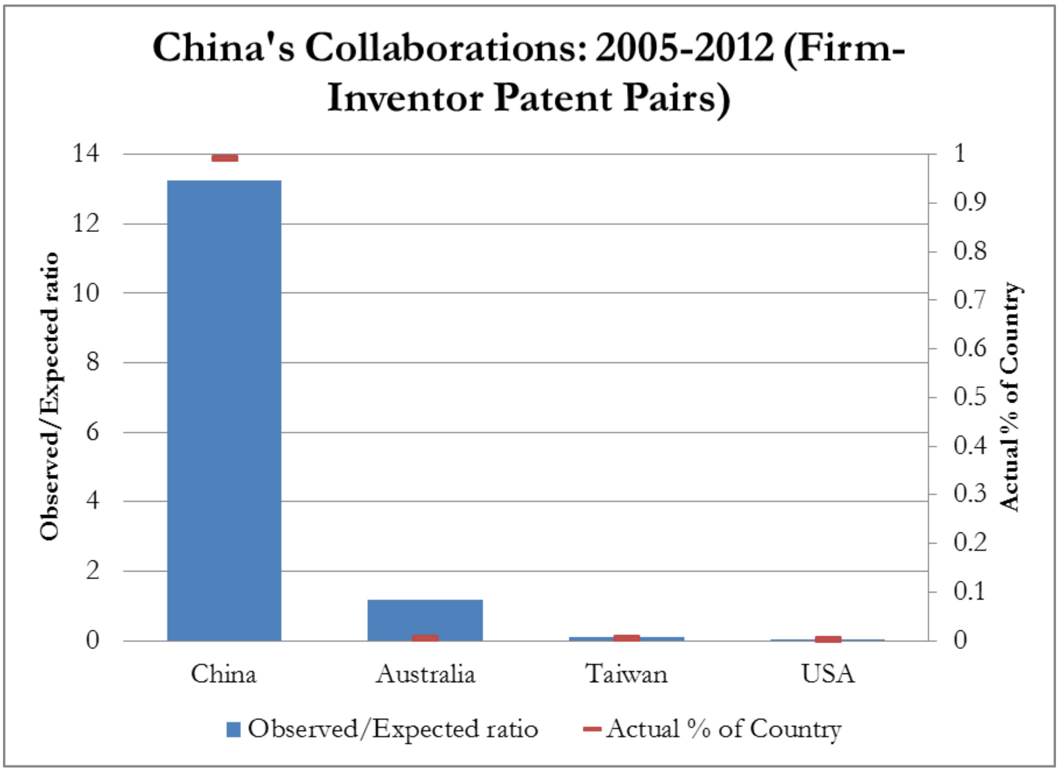
Source: Author's calculations from patents downloaded from PATSTAT database.



Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 9E. Patent collaborations between Chinese firms and domestic/foreign inventors in two time periods

Source: Author's calculations from patents downloaded from PATSTAT database.



Source: Author's calculations from patents downloaded from PATSTAT database.

4.4.4 USA: First-mover who is the most central network

In each of the networks featured in Section 2, the USA demonstrated its prominence as the most central node in the network. Whilst the USA is an important bridge of knowledge spillovers for all countries (demonstrated by it high betweenness centrality), the countries that are most relevant to the USA can receive the most benefit through having a higher interaction with the USA. Unlike other first-mover countries like Japan and Germany, the USA's most relevant partners are more geographically dispersed. These include Canada (a direct spatial neighbour), but also Australia, Taiwan, Sweden, and South Korea.

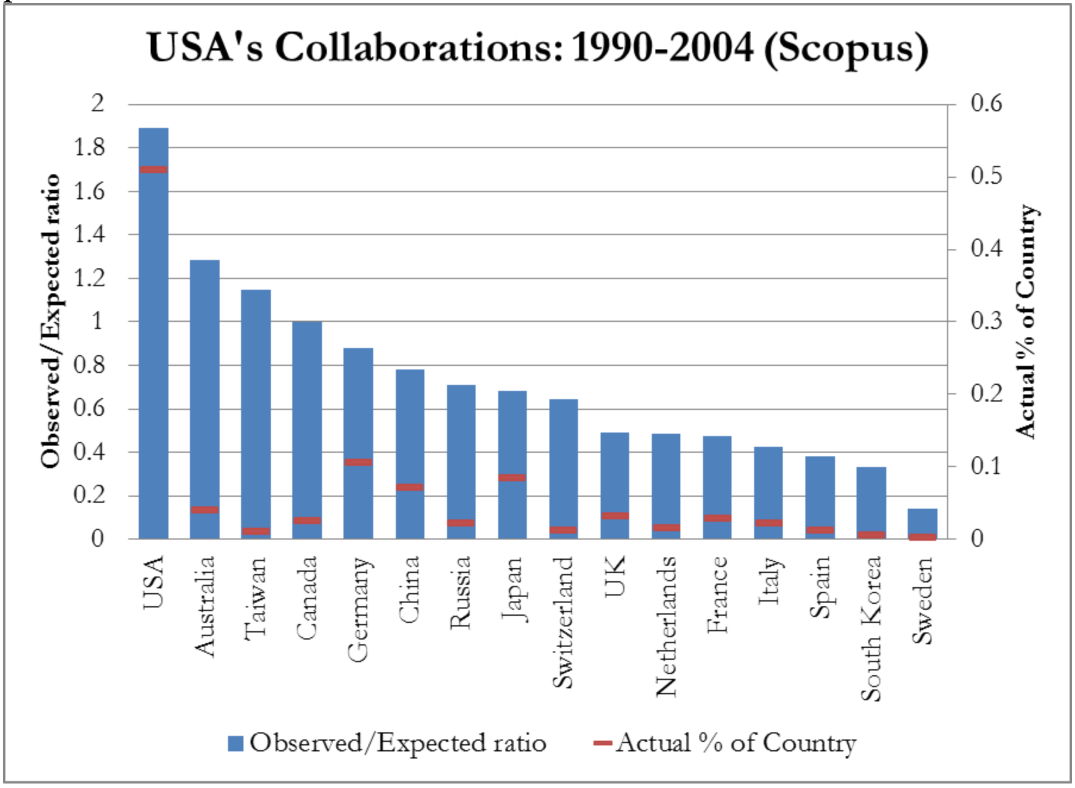
Out of this set of countries, one of the most striking findings is the relevance of Taiwan – especially as it exceeds even the USA itself in terms of inter-firm patent collaborations in the first period (see Figure 10D). This finding is striking because of the low centrality of Taiwan in all five research networks seen in Section 2. However for both research and patent collaborations, it does play an important role for the USA. In surveying the literature on Taiwan's strategies for increasing its own technological capabilities, two important factors are highlighted. Both Chen & Jaw (2009), Saxenian (2002), Wu & Mathews (2012) highlight the importance of Taiwanese diaspora networks in the USA which leverage both human and financial capital to facilitate technology transfers and research collaborations between the two countries. The purpose is to not only build the industrial capacity of Taiwan, but to engage in the circulation of knowledge between the two countries. What can be seen is that in the latter time period, Taiwan plays a less important role for the USA in all research datasets, except for firm-to-firm patent collaborations. Nevertheless Taiwan's high relevance as a partner to the USA demonstrates its indirect access to high-level knowledge spillovers – potentially bypassing the need to undertake direct research collaborations with several other countries.

Another interesting feature of the USA's collaboration profiles is how other first-mover countries with large industrial capacities (aside from Switzerland) do not feature in the top 3 partner countries in either time period. Although Germany is a mid-ranking country for the USA (especially in the second time period), Japan tends to be at the lower end. One possible explanation for this pattern is that both Germany and Japan have similar levels of product diversification (as can be seen in Chapter 3) (Carvalho & Perkins, 2015). One explanation for this pattern is that both Germany and Japan are similar to the USA in terms of their product diversification, therefore collaboration is less beneficial since there is less need to leverage knowledge complementarities/complementary resources. An alternative explanation is that since these countries compete directly in the commercialisation of more niche technologies, they may be less willing to share proprietary information. This hypothesis could be supported by the relative drop in ranking for both Japan and Germany in the latter time period for each patent dataset.

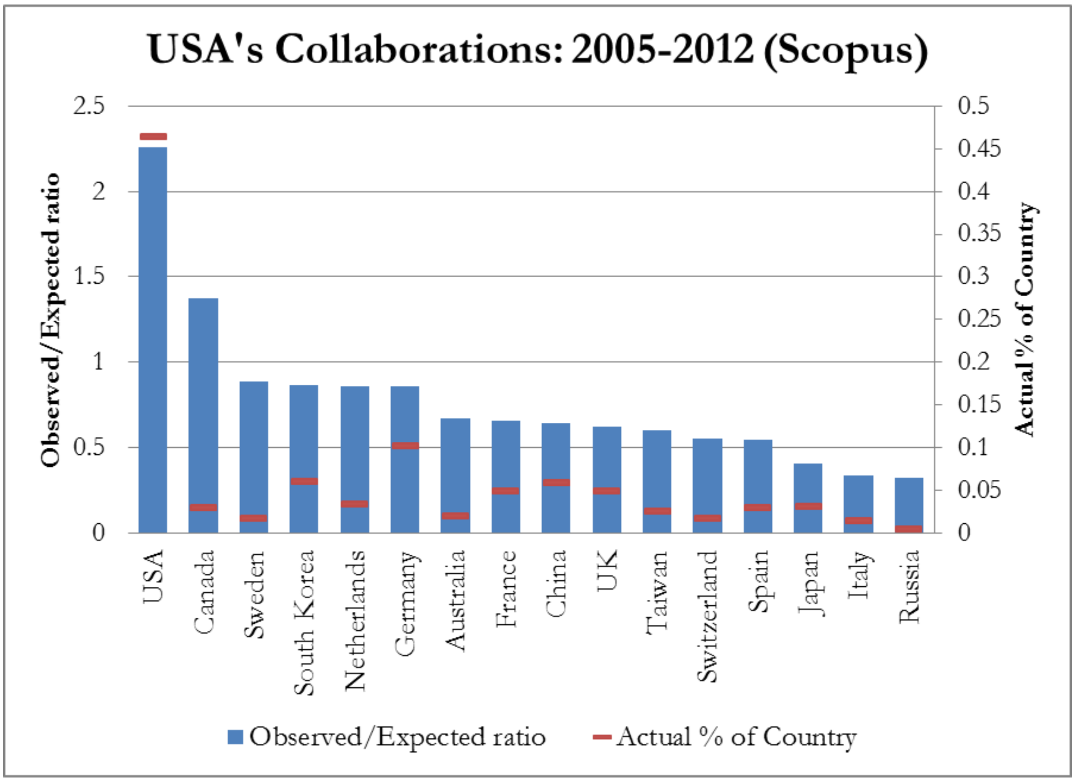
However another explanation could be that countries with a large industrial capacity may not be as collaborative as economies with smaller industrial capacities. In looking at the research partnership rankings of the USA, Germany, Japan, and China in each country's dataset, they are not as relevant as countries with smaller industrial capacities. This finding is surprising as it shows that first-mover countries do not collaborate with each other as often as might be suggested, despite these countries featuring prominently in the hierarchy within networks (suggested by their high eigenvector centrality in the latter period). These findings, along with their collaborations with other countries that are less competitive in terms of industrial capacity, highlight how the competitive dynamics of the domestic industry can potentially affect who these countries collaborate with.

Figure 10. USA's profiles of country partners in two time periods

Figure 10A. Scopus research collaborations with American authors in two time periods

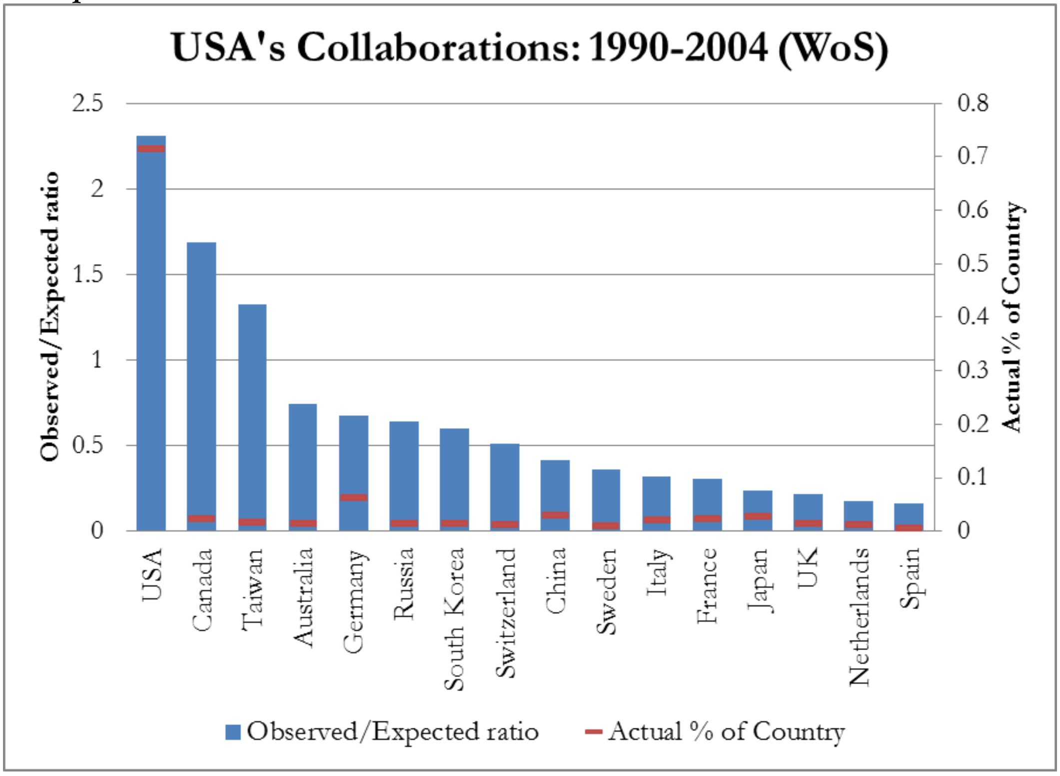


Source: Author's calculations from research publications downloaded from Scopus.

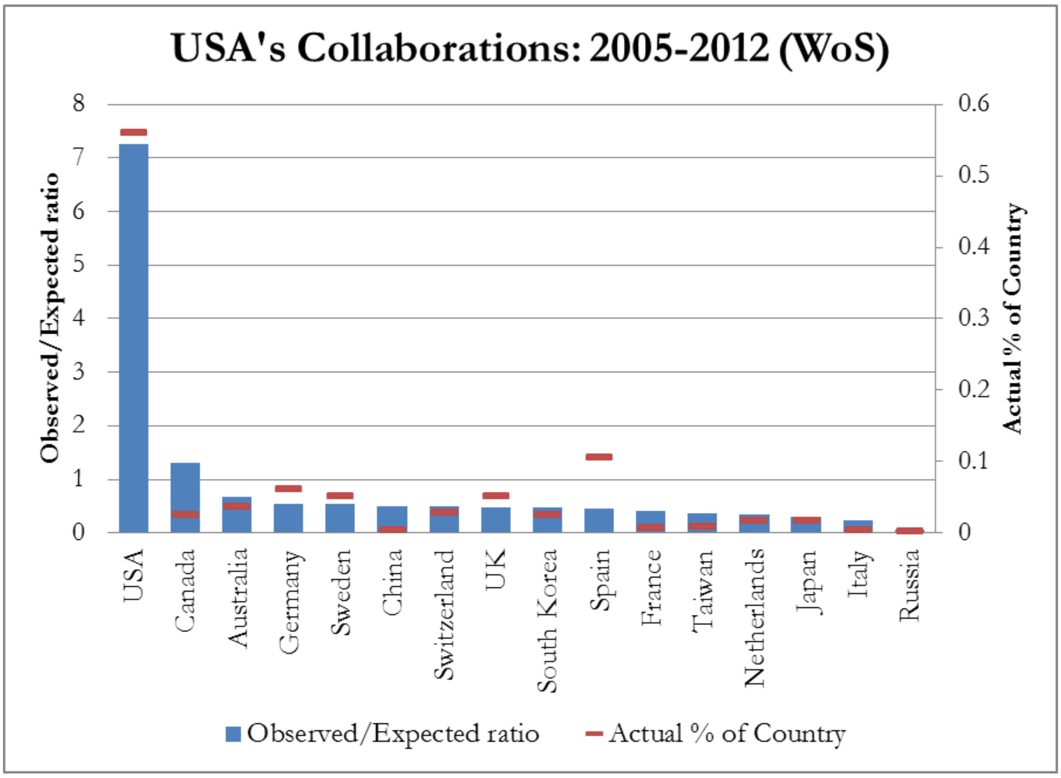


Source: Author's calculations from research publications downloaded from Scopus.

Figure 10B. Web of Science research collaborations with American institutions in two time periods

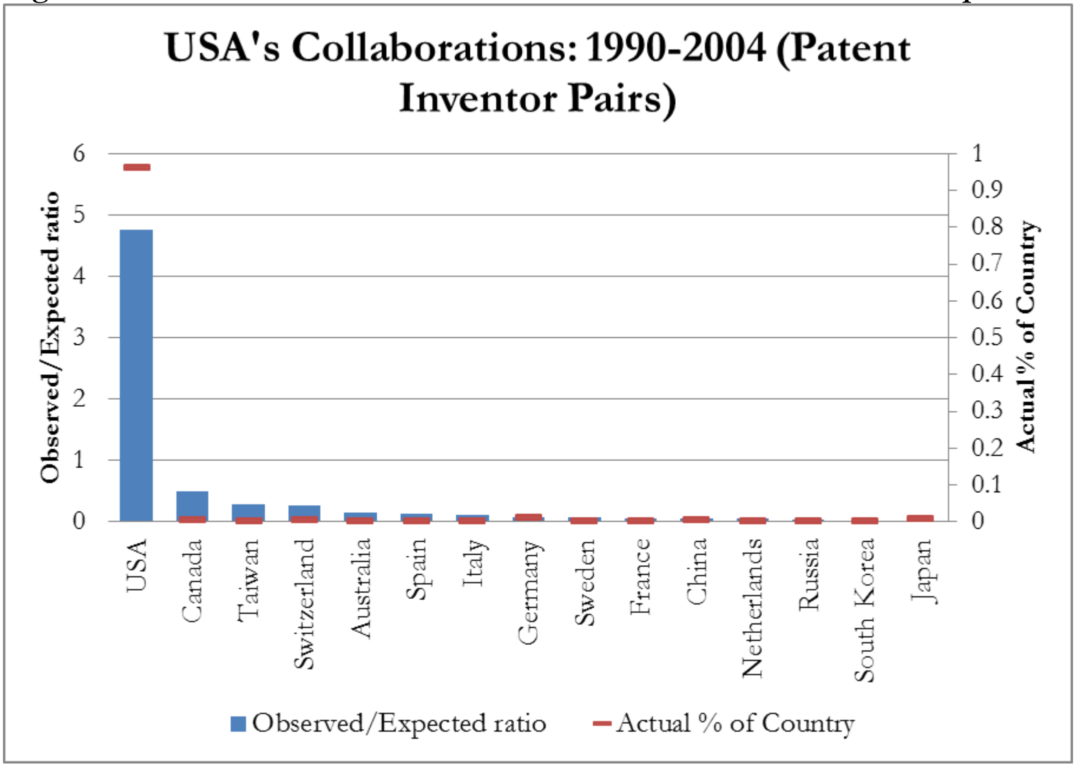


Source: Author's calculations from research publications downloaded from Web of Science.

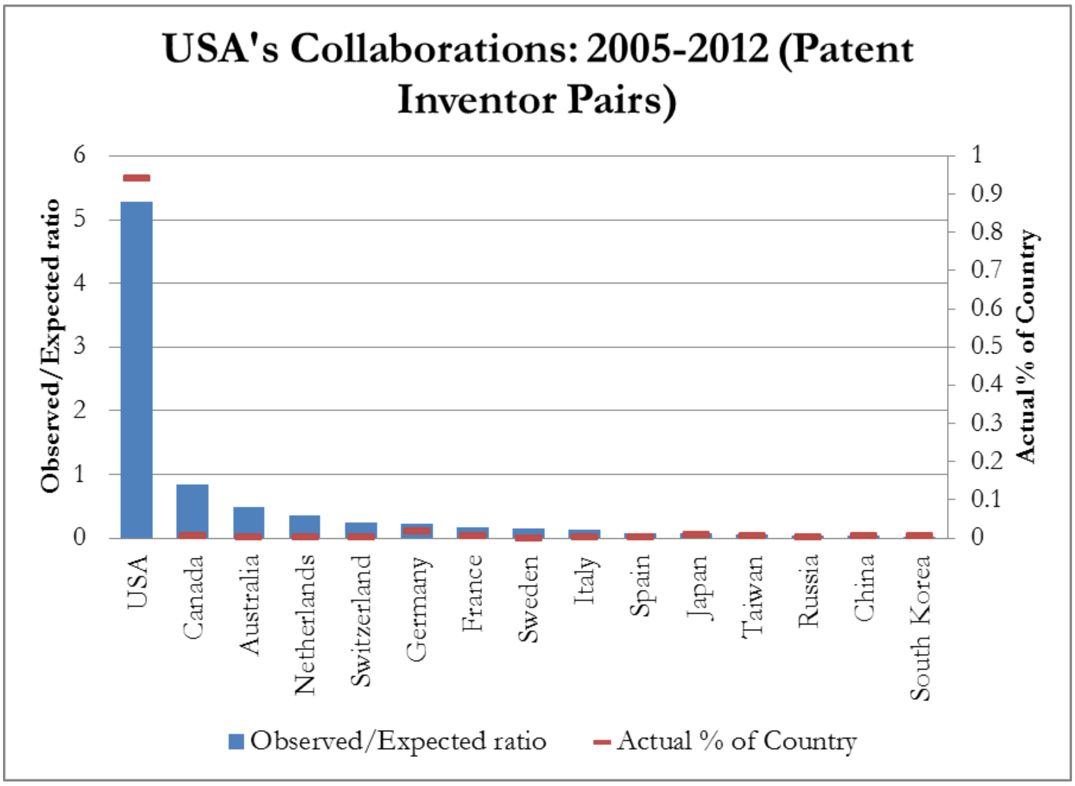


Source: Author's calculations from research publications downloaded from Web of Science.

Figure 10C. Patent collaborations with American inventors in two time periods

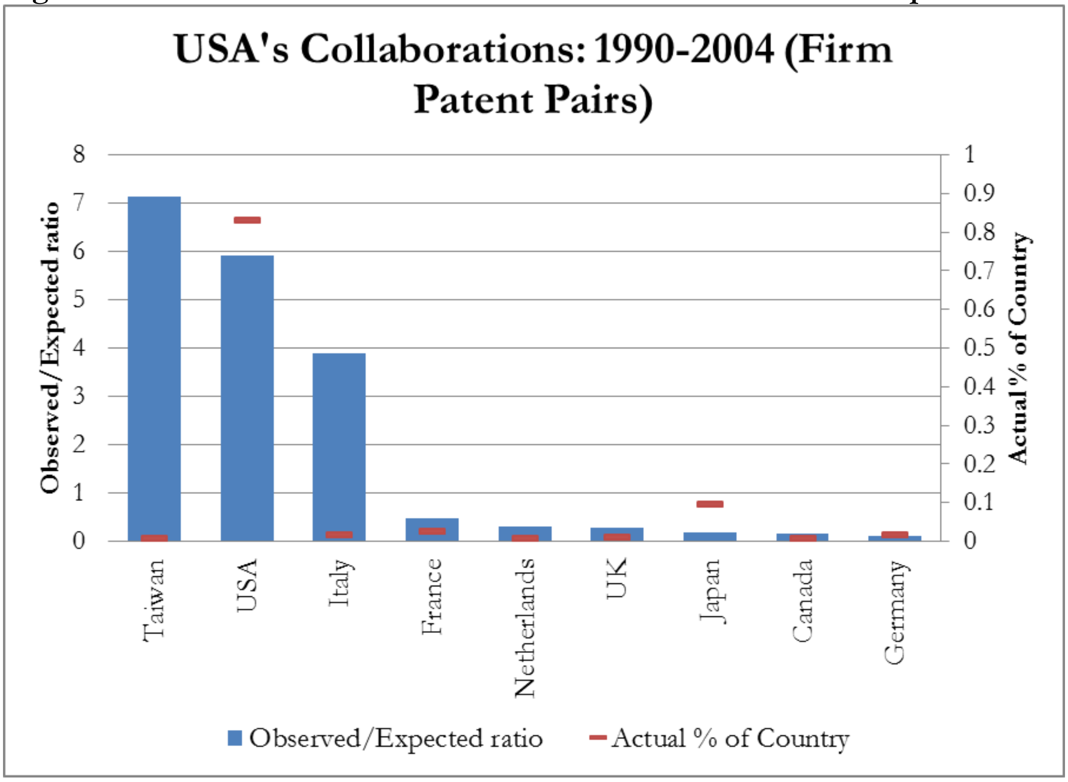


Source: Author's calculations from patents downloaded from PATSTAT database.

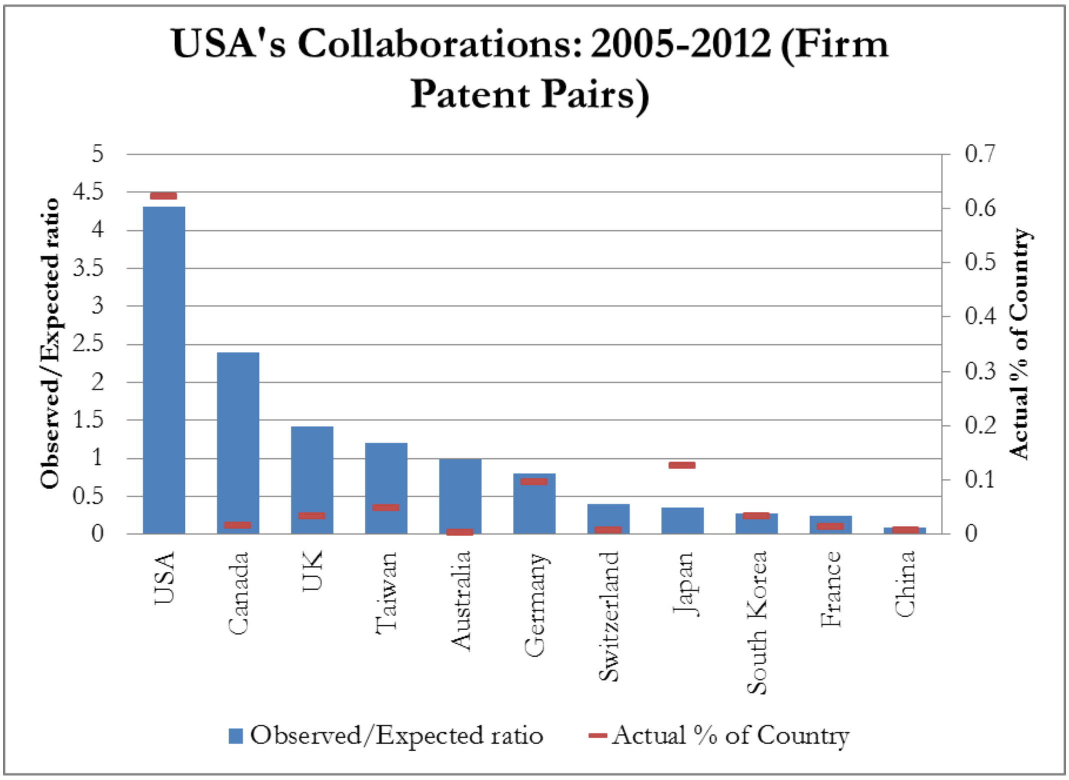


Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 10D. Patent collaborations with American firms in two time periods

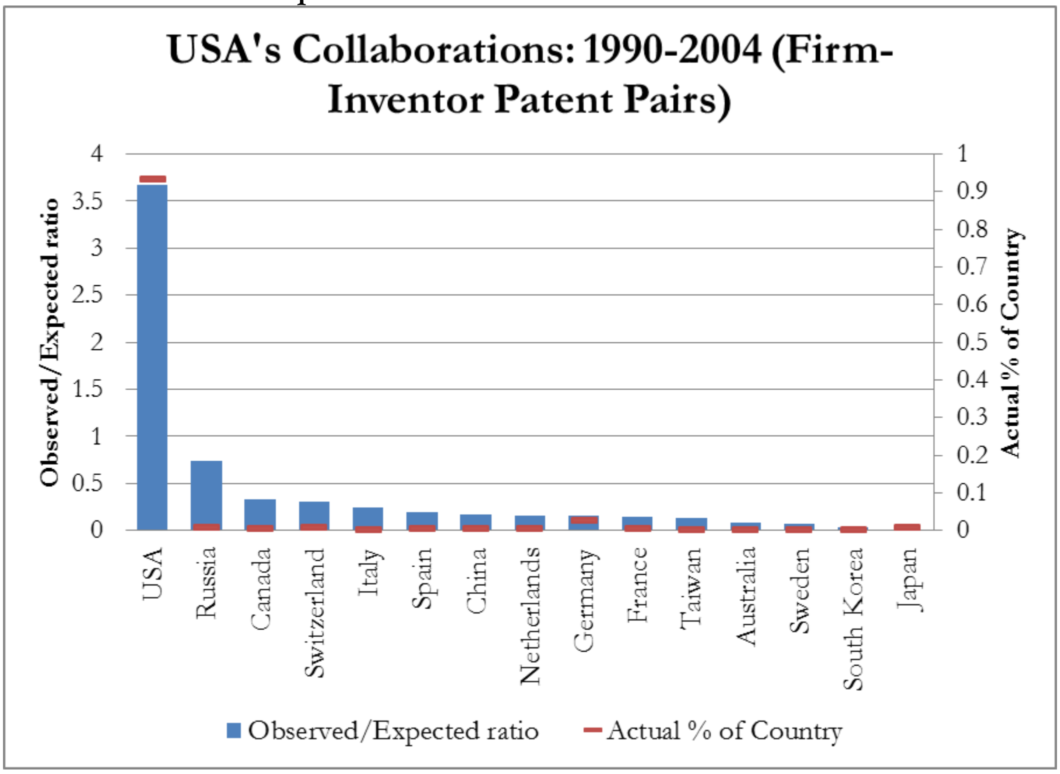


Source: Author's calculations from patents downloaded from PATSTAT database.

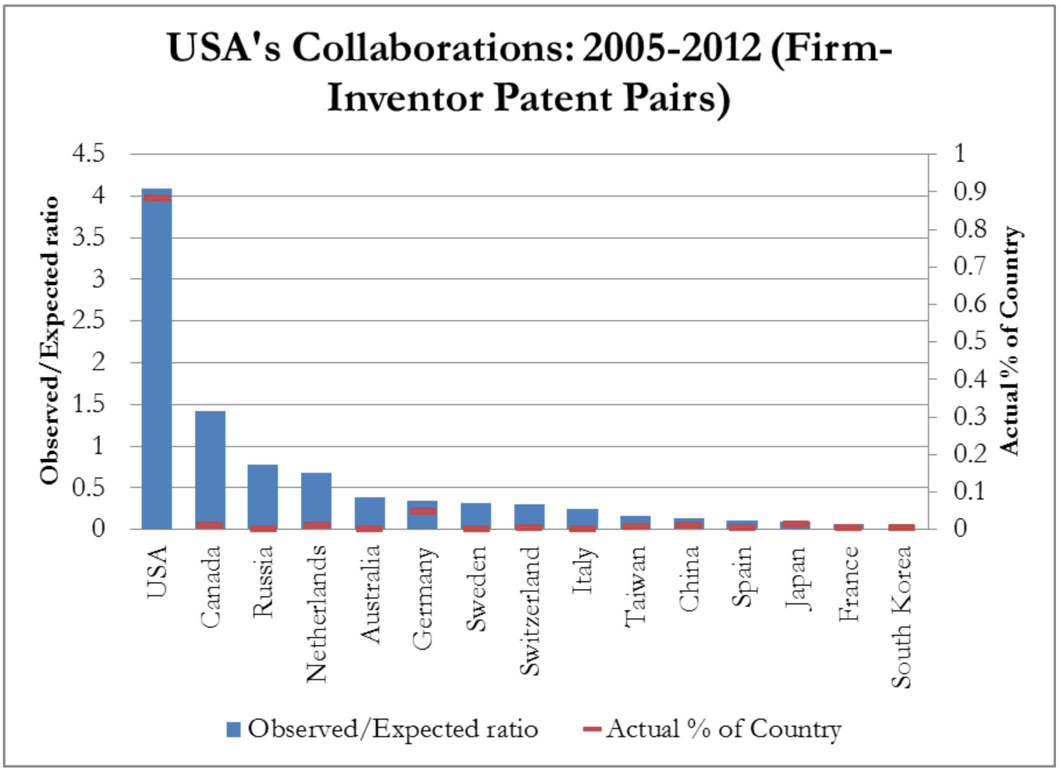


Source: Author's calculations from patents downloaded from PATSTAT database.

Figure 10E. Patent collaborations between American firms and domestic/foreign inventors in two time periods



Source: Author's calculations from patents downloaded from PATSTAT database.



Source: Author's calculations from patents downloaded from PATSTAT database.

4.5 Conclusion. Discussion of findings and implications for future research

This chapter has studied the evolution of first-mover and late-comer countries in accordance with their centrality within different innovation networks of solar PV, and who they collaborate, in two time periods. The purpose was to investigate certain implicit hypotheses that are within the existing literature from EEG and international development on the structure of these networks, and the collaboration profiles of different countries, based on their technological capabilities. EEG posits that countries with high technological capabilities are more likely to collaborate with each other than those with low technological capabilities – given the need to have similar levels of capabilities to undertake research at the technological frontier (Asheim & Isaksen, 2002; Coe & Bunnell, 2003; Matthiessen et al., 2010). The international development literature recognises that countries with lower technological capabilities will undertake research collaborations with countries with high technological capabilities in order to benefit from more high-level knowledge spillovers (Fan & Hu, 2007; Hu, 2012; Kim & Tunzelmann, 1998). The experience from these research collaborations would increase the technological capabilities of late-comer (Bell & Albu, 1999; Ockwell, Sagar, & de Coninck, 2014).

Both of these literatures highlight how international research collaborations provide a key form of knowledge spillovers that can increase the technological capabilities of both first-mover and late-comer countries (Beaver & Rosen, 1978; Katz, 1994; Lewis, 2014; Luukkonen et al., 1992). In testing these hypotheses, the chapter identifies the USA, Germany and Japan as being both first-movers and having large industrial capacity. This categorisation is justified, especially given these countries' contributions to global research and manufacturing (as shown in Chapter 3) (Carvalho & Perkins, 2015). As a late-comer, it recognises that whilst China has a lower technological capability than these other countries, its capabilities appear to be increasing. In looking at these countries positions within the different solar PV innovation networks, it does recognise the difference between countries' positions in scientific research publications versus patents. Whilst the former shows the rise of China's centrality within these networks, the latter shows that China is less central within patent networks. This result could be due to China having a comparatively lower contribution to patent research (Carvalho & Perkins, 2015). With regards to looking at international research collaborations for patents, the lower centrality of China in comparison to the other countries would imply it would benefit less from knowledge spillovers from industrial research.

However what is more surprising is the pattern of partner country profiles of these countries. Though USA, Germany and Japan have high technological capabilities, these countries do not feature prominently in the top relevance of countries. Of course, one explanation for Germany is that it collaborates more with its European neighbours, demonstrating the continued importance of spatial proximity in international collaborations. What is equally surprising is that USA, Germany, and Japan do no feature as prominently for China as research partners. This appears to contradict initial thesis from the international development literature – which highlights that late-comers seek research collaborations with countries that are most central in the network (Ernst, 2006; Kim & Tunzelmann, 1998; Mathews & Cho, 2000). Though arguably Japan is not as central within the network (as seen in the centrality tables in the Appendix), it is actually spatially close to China to enable research collaborations. A common pattern in all of these countries' profiles is the importance of other countries who do have high technological capabilities, but lower industrial capacity.

Bearing in mind that these results are preliminary, it does raise important questions on how the size of domestic industries can affect international research collaborations. Considering that each of these countries' analysed have high industrial capacity, could competitive dynamics of the industries lead to these actors collaborating less with each other than would be originally assumed? This factor would be interesting, as innovative actors would want to ensure that knowledge spillovers increase the competitiveness of domestic industrial capacity over foreign competitors. Therefore the political economy – and more specifically, techno-nationalism – could affect the pattern of international research collaborations, something that the EEG literature has yet to explicitly explore. The political economy factor could potentially explain prominence of countries such as Australia, Switzerland, and Canada – which have comparatively smaller industrial capacities but high technological capabilities. As these countries do have high technological capabilities from research, they are attractive to collaborate with. However their comparatively lower industrial capacity does not necessarily threaten the competitiveness of domestic industry – thus removing the political economy consideration. In order to explore these patterns, future research should also look at the research collaboration profiles of these countries. Qualitative methodologies of interviewing actors in the different cross-section of technological capabilities and industrial capacity would thus be useful in exploring whether political economy factors can influence patterns of research collaborations.

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4.7 Appendix Tables

Table A1. *Scopus*: Centrality measures of countries in each time period

	Degree		Betweenness Centrality		Eigenvector Centrality	
Countries	1990-2004	2005-2012	1990-2004	2005-2012	1990-2004	2005-2012
USA	17.00	17.00	15.98	0.49	0.09	0.07
China	13.00	17.00	7.14	0.49	0.07	0.07
Germany	15.00	17.00	4.62	0.49	0.08	0.07
UK	14.00	17.00	3.13	0.49	0.08	0.07
France	13.00	17.00	1.28	0.49	0.08	0.07
Australia	9.00	17.00	1.07	0.49	0.05	0.07
South Korea	7.00	17.00	0.17	0.49	0.03	0.07
Spain	10.00	17.00	0.11	0.49	0.06	0.07
Switzerland	12.00	16.00	1.50	0.33	0.07	0.06
Canada	7.00	16.00	0.00	0.33	0.04	0.06
Japan	12.00	16.00	2.92	0.32	0.06	0.06
Italy	15.00	16.00	4.97	0.23	0.08	0.06
Netherlands	11.00	16.00	0.84	0.23	0.06	0.06
Sweden	11.00	15.00	0.24	0.15	0.07	0.06
Russia	12.00	15.00	1.03	0.33	0.07	0.06
Taiwan	4.00	14.00	0.00	0.15	0.02	0.05

Source: Calculated from Scopus database

Table A2. *Web of Science*: Centrality measures of countries in each time period

Countries	Degree 1990-2004	Degree 2005-2012	Betweenness Centrality 1990-2004	Betweenness Centrality 2005-2012	Eigenvector Centrality 1990-2004	Eigenvector Centrality 2005-2012
Australia	11.00	17.00	1.54	0.52	0.06	0.07
China	11.00	17.00	4.98	0.52	0.05	0.07
France	13.00	17.00	1.10	0.52	0.07	0.07
Italy	15.00	17.00	3.87	0.52	0.08	0.07
Japan	13.00	17.00	2.59	0.52	0.07	0.07
South Korea	7.00	17.00	0.17	0.52	0.03	0.07
Spain	12.00	17.00	0.22	0.52	0.07	0.07
UK	15.00	17.00	4.31	0.52	0.08	0.07
USA	17.00	17.00	15.37	0.52	0.08	0.07
Canada	7.00	16.00	0.98	0.26	0.03	0.06
Germany	14.00	16.00	1.64	0.26	0.08	0.06
Netherlands	12.00	16.00	0.38	0.26	0.07	0.06
Switzerland	12.00	16.00	0.38	0.26	0.07	0.06
Sweden	12.00	15.00	0.22	0.00	0.07	0.06
Russia	14.00	14.00	3.26	0.17	0.08	0.05
Taiwan	5.00	14.00	0.00	0.17	0.02	0.05

Source: Calculated from Web of Science database

Table A3. Co-Inventors: Centrality measures of countries in each time period

Countries	Degree 1990-2004	Degree 2005-2012	Betweenness Centrality 1990-2004	Betweenness Centrality 2005-2012	Eigenvector Centrality 1990-2004	Eigenvector Centrality 2005-2012
Germany	13.00	16.00	10.52	11.12	0.11	0.10
USA	16.00	16.00	32.10	11.12	0.12	0.10
France	9.00	12.00	1.87	2.60	0.08	0.08
South Korea	6.00	12.00	0.25	3.39	0.05	0.08
Switzerland	10.00	11.00	2.43	1.86	0.09	0.07
China	9.00	11.00	2.78	2.28	0.08	0.07
Netherlands	6.00	11.00	0.20	2.41	0.05	0.07
Canada	11.00	11.00	8.70	3.31	0.09	0.07
Japan	7.00	10.00	0.20	1.55	0.07	0.07
Spain	7.00	9.00	0.50	0.90	0.06	0.06
Sweden	4.00	8.00	0.00	0.53	0.03	0.05
Italy	7.00	8.00	0.20	0.48	0.06	0.05
Australia	5.00	7.00	0.00	0.17	0.04	0.05
Russia	6.00	7.00	0.25	0.14	0.05	0.05
Taiwan	4.00	7.00	0.00	0.14	0.03	0.04

Source: Calculated from PATSTAT database

Table A4. Intra-Firm Networks: Centrality measures of countries in each time period

	Degree		Betweenness Centrality		Eigenvector Centrality	
	1990-2004	2005-2012	1990-2004	2005-2012	1990-2004	2005-2012
Countries						
USA	10.00	12.00	22.60	23.83	0.13	0.13
Germany	9.00	9.00	14.70	4.92	0.12	0.11
China	3.00	10.00	0.00	12.25	0.02	0.11
France	8.00	8.00	7.90	5.67	0.11	0.09
Japan	8.00	7.00	3.90	1.58	0.12	0.09
South Korea	2.00	7.00	0.00	0.67	0.00	0.09
Switzerland	7.00	8.00	11.60	15.92	0.09	0.08
Netherlands	6.00	6.00	0.00	0.83	0.09	0.07
UK	8.00	6.00	1.60	0.83	0.12	0.06
Taiwan	1.00	5.00	0.00	0.00	0.02	0.06
Canada	8.00	5.00	6.70	0.00	0.11	0.05
Australia	3.00	4.00	0.00	0.00	0.02	0.04
Sweden	2.00	4.00	0.00	0.50	0.00	0.03
Italy	3.00	3.00	0.00	0.00	0.02	0.01
Spain	4.00	2.00	0.00	0.00	0.04	0.00
USA	10.00	12.00	22.60	23.83	0.13	0.13
Germany	9.00	9.00	14.70	4.92	0.12	0.11

Source: Calculated from PATSTAT database

Table A5. Firms and Inventor networks: Centrality measures of countries in each time period

Countries	Degree 1990-2004	Degree 2005-2012	Betweenness Centrality 1990-2004	Betweenness Centrality 2005-2012	Eigenvector Centrality 1990-2004	Eigenvector Centrality 2005-2012
Germany	15.00	17.00	13.63	12.09	0.09	0.09
USA	17.00	17.00	21.24	12.09	0.10	0.09
Switzerland	13.00	14.00	5.46	5.09	0.09	0.08
France	10.00	13.00	1.48	3.29	0.07	0.08
Netherlands	10.00	13.00	0.90	2.66	0.07	0.08
South Korea	7.00	13.00	0.38	4.49	0.04	0.07
Japan	11.00	12.00	3.58	1.88	0.07	0.07
China	10.00	11.00	2.20	1.75	0.07	0.06
UK	10.00	10.00	4.85	3.65	0.07	0.06
Canada	10.00	9.00	4.07	0.00	0.06	0.06
Italy	7.00	9.00	0.00	0.40	0.05	0.05
Spain	8.00	9.00	0.53	0.25	0.06	0.05
Australia	7.00	8.00	0.58	0.24	0.05	0.05
Taiwan	6.00	7.00	0.00	0.00	0.04	0.04
Sweden	5.00	6.00	0.00	0.00	0.03	0.03
Russia	6.00	6.00	0.13	0.13	0.04	0.03

Source: Calculated from PATSTAT database

Chapter 5: How does the presence – or absence – of domestic industries affect the commercialisation of technologies?

A comparative approach to how the maturity of technologies and the domestic industrial composition affects the propensity for actors to collaborate with domestic or foreign partners.

Abstract. The literature in evolutionary economic geography (EEG) highlights the importance of the spatial proximity between research institutes and industrial firms in facilitating learning feedback between these different types of actors when engaging in commercialisation for early stage technology. This literature assumes the existence of domestic industries to enable these commercialisation efforts. This chapter considers the importance of domestic industry in enabling innovation efforts for different solar photovoltaic (PV) technologies. It demonstrates how the professionalisation of solar PV sciences and the spread of solar PV social networks has enabled innovators and industrial actors to 'search for the right partners' in early-stage research for alternative PV technologies. While there is no guarantee, the presence of domestic industries with diverse skill sets can increase the probability of finding a partner with the right knowledge complementarities. These preliminary findings also illustrate how strong linkages between research institutes and domestic industries can *intentionally* limit international knowledge spillovers that can help foreign industrial partners to compete with domestic industries. In contrast, the absence of domestic industrial linkages incentivises research institutes to seek foreign industrial partners for commercial collaborations.

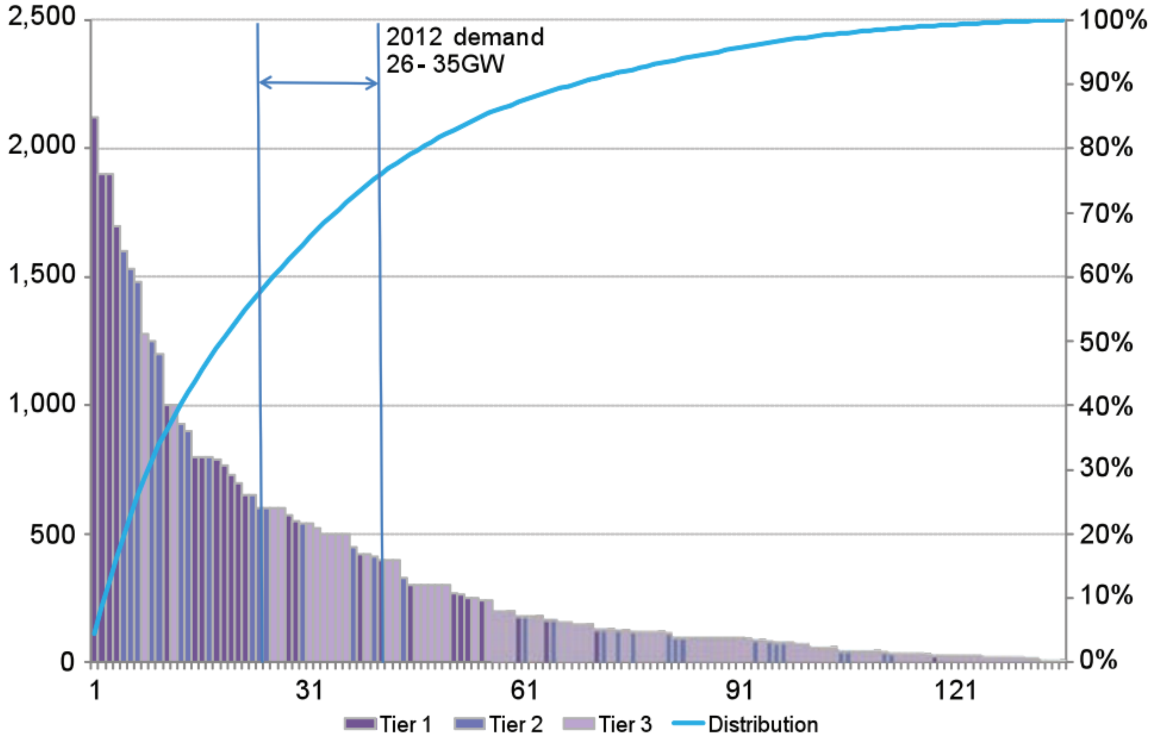
5.1 Introduction

Evolutionary economic geography (EEG) demonstrates how economies become resilient to global competition by developing more innovative technologies (Maskell & Malmberg, 1999; Storper, 1997; Swanstrom, 2008) and retaining high-value industrial activities (Asheim & Coenen, 2006). In doing so, these economies can adapt to the loss of mature technology manufacturing as they shift to lower cost economies. By spatially embedding innovation within the domestic economy, countries can develop the next generation of technologies (Audretsch & Feldman, 1996). Alternatively, the domestic economy can concentrate on high-level process innovations (Bailey & Bosworth, 2014; EU Commission, 2012) that improve the production efficiencies and quality of technologies. However EEG cautions that the path-dependent nature of technological accumulation can lock economies into innovating along specific technological trajectories (Boschma & Martin, 2010). Economies that led the innovation of a specific technology can become vulnerable to disruptive innovations introduced by another economy.

This chapter focuses on how industrial diversity enables the resilience of economies by introducing *disruptive* innovations. Disruptive innovation is related to J. A. Schumpeter's notion of 'creative destruction', where incumbent firms and industries are replaced by newer, more innovative firms (Schumpeter, 1975). Schumpeter ascribes this industrial dynamism to the competitiveness of innovative firms and their associated technologies. Domestic industries can achieve a level of resilience if they successfully commercialise technologies that other economies cannot replicate. As Chapter 2 argues, industries that only manufacture replicable incumbent technologies are less likely to be resilient to global competition in the long run. The replicability of technologies in different economies exposes them to global supply and demand dynamics (Masahiko & Haruhiko, 2002). Although these technologies can still appropriate large shares of the market, margins of economic value diminish. In contrast, firms (and their associated industries) that commercialise alternative technologies can achieve higher levels of value-added (Porter, 2011). These alternative technologies have yet to become replicable due to proprietary ownership.

The global solar photovoltaic (PV) industry provides a good case study for exploring how the nature of industrial dynamism affects economies' resilience to global competition. The vast majority of solar PV demand is met by crystalline PV technologies (Goodrich, James & Woodhouse, 2011). However, the global oversupply of crystalline PV technologies led to diminished, and even negative, profit margins for most firms involved in this value chain (Chase, 2013). Established 'Tier 1' solar PV firms (i.e. those proven to have high quality technologies) have survived, but many 'Tier 2' and 'Tier 3' players have gone bankrupt (see Figure 1). In contrast, two firms producing alternative PV technologies have managed to achieve profitable margins during this time. Their success in commercialising alternative PV technologies is due to lower production costs relative to crystalline PV (see Figure 2 in Chapter 2).

Figure 1. Nameplate cell manufacturing capacity of companies by rank (MW and distribution in meeting demand)



*Source: BNEF (2012:, p. 5). *Note: This was reported as of 12 May 2012*

This chapter explores how different actors engage with domestic and foreign networks in efforts to commercialise different solar PV technologies. It draws on interviews with research institutes and firms in various countries, who are involved with the innovation of crystalline PV and/or alternative solar PV technologies. These interviewees are located in economies that have the presence – or absence – of a domestic solar PV industry. This chapter is similar to Chapter 4 in terms of using a comparative approach based on the industrial composition of countries. However Chapter 4 uses scientific publications and patents to spatially delineate these research collaborations. This approach has it limits because it does not capture the tacit forms of knowledge exchange occurring through social networks of innovative actors. Second, these indicators only represent research collaborations to the exclusion of commercialisation efforts. Interviews, however, can provide insight into these tacit interactions in the commercialisation process of different PV technologies.

This chapter can thus include an analysis of commercialising efforts based on different categories of industrial composition and maturity of technologies. The literature from EEG largely assumes that in the early stage of commercialisation, interactions between innovative actors and industrial actors need to be spatially proximate (Audretsch & Feldman, 1996). In contrast, the spatial relationship between innovation and manufacturing can be spatially distant for mature technologies (Vernon, 1966). This chapter's comparative approach yields preliminary findings that appear to contradict the existing hypotheses. It demonstrates that even at the early stages, cooperation between research and industrial actors can occur transnationally. What appears to be more important is a high level of knowledge complementarity between partners. By contrast, the presence of a domestic industry can raise an inherently techno-national perspective of foreign research collaborations where more mature technologies are concerned. The absence of a domestic industry not only eliminates this concern, but can even facilitate foreign collaborations. Therefore these findings indicate how the nature of the domestic industry can either limit or facilitate knowledge spillovers across national borders.

The purpose of this research is to examine whether innovative actors need access to domestic industry in order to advance domestic efforts into solar PV innovation. Section 2 looks at challenges in commercialising technologies, with a particular focus on the spatial dynamics between innovation and manufacturing. Section 3 illustrates why the solar PV industry is a good case study to explore these questions and describes the methodology. Section 4 discusses the main findings. The concluding section focuses on the implications of these findings for the wider literature on EEG and green growth.

5.2 Does the commercialisation of technologies need access to domestic manufacturing?

This section starts by looking at the motivation for analysing the spatial relationship between innovation and manufacturing. Using the literature on the systems failure approach to innovation systems, it demonstrates how countries' ability to commercialise product innovations is based on 'scaling' production. Scaling production implies access to industries that can develop technological equipment to manufacture a high volume of final products (or sub-components) (Huijben & Verbong, 2013). In additional to the theoretical literature that eschews geographical perspectives on technological transitions, associated empirical studies on the commercialisation process tend to focus on countries with domestic industries. EEG provides a useful perspective on the spatial evolution of industrial activities based on the maturity of technologies (Boschma & Frenken, 2006; Vernon, 1966). Therefore EEG is useful in demonstrating how the maturity of technologies affects the spatial distance between innovation and manufacturing. The following section integrates these insights into a conceptual framework and concludes by recognising that there is a gap in the literature in terms of how the presence (or absence) of domestic industry influences the nature of research-industry partnerships.

5.2.1 The importance of scaling in commercialising technologies

The systems failure approach to innovation systems focuses on how the lack of linkages between key actors leads to the failed commercialisation of product innovations – especially with regards to "crossing the valley of death" (Geels, 2002; Woolthuis, Lankhuizen, & Gilsing, 2005). Innovation systems characterises how innovative actors operate within various networks and institutions to undertake innovations – including bringing these technologies to the market. The systems failure approach focuses on various imperfections within the innovation systems that inhibit innovation efforts. For this issue, the most relevant are transitions failure, and weak and strong network failures (Carlsson et al., 2002). The "valley of death" analogy refers to the financing gap in the middle stages of the innovation process involved with revising early demonstration technologies (Markham et al., 2010). There are several challenges in enabling market commercialisation. The first is demonstrating that these technologies actually *function* outside of a laboratory setting, which requires the development of prototypes for field testing and obtaining feedback from early users of technologies (Schot & Geels, 2008).

The systems failure approach recognises entrepreneurs as important actors in seeking commercial applications for prototypes (Auerswald, 2012). This approach recognises that economies that lack these kinds of actors – and their networks – can produce a lot of promising product innovations that "remain on the shelf" – highlighting a weak network failure (Woolthuis, Lankhuizen & Gilsing, 2005). Entrepreneurs' ability to raise financing for scaling production is extremely difficult. A comprehensive survey of clean energy investors by BNEF (2010) demonstrates there are not many investors who match the risk tolerance and capital requirements required at this stage of technology development.

Another key issue for the commercialisation of *disruptive* (or at least, alternative) product innovations is to ensure that they are competitive with incumbent technologies (Unruh &

Einstein, 2000). The attractiveness of disruptive innovations is that they provide technological performance that is superior to incumbent technologies (Klepper, 1996). Nonetheless, the potential for these technologies to displace incumbent technologies can be hampered by techno-institutional lock-in effects of incumbent technologies – demonstrating strong network failures (Stern & Rydge, 2013). These 'lock-in' effects refer to factors such as supportive infrastructures or user behaviours that reinforce the preference for incumbent technologies. Strategic niche management (SNM) studies emphasise the creation of 'protected market spaces' for learning feedback loops between producers and potential users (Verbong, Geels & Raven, 2008). This feedback can modify the design and functionality of technologies to meet customer preferences/needs, and even their safety (e.g. pharmaceutical industries). User-producer linkages are also important in integrating clean energy technologies into the larger energy infrastructure (Cowan & Hultén, 1996; Unruh, 2002).

The second challenge is the actual scaling of production, which can require the development of specialised production equipment for manufacturing (Huijben & Verbong, 2013). It can also include retooling existing manufacturing plants to accommodate product innovations (Tamayo-Torres, Gutierrez-Gutierrez & Ruiz-Moreno, 2014). Achieving scalability is especially important in terms of ensuring that disruptive technologies go beyond niche technologies to large-scale market diffusion (BNEF, 2010). An important factor that prevents alternative innovations from displacing incumbent technologies is their higher costs of production (Argote, 1993). These high production costs are not necessarily due to being inherently more expensive to produce than incumbents (McDonald & Schrattenholzer, 2001), but because of low production volumes. Standard microeconomic theory demonstrates that economies of scale are achieved by increasing production volume to a point where average unit costs decline. Furthermore, increasing production enables learning-by-doing processes that further enable the commercialisation of technologies (Jovanovic & Rousseau, 2002). Learning curves were thus developed as a concept for measuring productivity improvements or cost reductions associated with increases in production capacity (Klenow, 1998).[5]

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[5]Ibenholt (2002, p. 1182) demonstrates how "cost reductions are driven by five factors: (1) technological progress; (2) input price changes; (3) internal-efficiency improvements; (4) learning-by-doing; (5) economies of scale."

Empirical studies on clean energy technologies demonstrate how these technologies have rapidly progressed along the learning curve. Goldemberg et al. (2004) describes how the Brazilian Alcohol Program provided producer subsidies to ethanol producers whilst setting fuel prices for gasoline. These policies encouraged the increase in ethanol production which reduced costs to a point where subsidies were no longer needed. Bazilian et al.'s (2012) study of crystalline PV measures how the prices for technologies (measured in dollars per watt) reduced by 67% from 2003 to 2012 with increases in production volume. Due to these reductions in cost and high domestic electricity prices, crystalline PV electricity generation became price competitive in countries such as Germany, Spain, Italy and Denmark. Solar PV's achievement of grid parity in these markets means that it no longer requires subsidies to compete with conventional electricity generation. However Nemet's (2006) study of solar PV learning curves, and Ibenholt's (2002) comparison of wind learning curves in European countries, demonstrate how *excessive* demand can thwart cost reductions. A good example is crystalline PV whose prices increased above the learning curve around 2003 due to demand exceeding supply, even with increased production capacity (see Figure 2 in Chapter 2). These studies demonstrate that the commercialisation of clean energy technologies suffers from production scalability issues (BNEF, 2010; Jamison, 2010).

This section briefly reviewed the challenges in commercialising product innovations – particularly with regard to scaling. A major challenge with scaling is access to industry with the necessary production technologies and engineering expertise. The difficulty is that there may be no investment to build a domestic industry for this technology due to high capital costs or lock-in effects. Second, the domestic economy may not have industrial players with the right knowledge complementarities to scale these technologies. So does the lack of a domestic industry mean the products of innovative economies just remain on the shelf?

5.2.2 How the maturity of technologies affects spatial distance between innovation and manufacturing

Evolutionary economic geography provides analysis on how the spatial relationship between innovation and manufacturing changes as technologies mature (Boschma & Frenken, 2006). During the early stage of scaling new product innovations, innovation and manufacturing tend to be closely clustered (Klenow, 1998). This spatial proximity is required to enable tacit exchanges of feedback between scientists and industrial actors in developing appropriate production technologies (Breschi & Lissoni, 2001). Alternatively, scientists can work with industrial players (e.g. engineers) in developing or retooling their production facilities to enable the scaling of new product innovations.

EEG also demonstrates that spatial proximity between innovation and manufacturing is reinforced by differences between scientists and industrial players. Ponds, van Oort & Frenken's (2007) study of collaborations between universities, governments and firms in the Netherlands shows that there is a correlation between organisational differences and closer spatial proximity. Their study argues that increased levels of communication and clarification are required between collaborative actors that have different organisational backgrounds. Similarly, Gittleman & Wolff (1995) demonstrate that a higher level of communication is required because scientists and industrial firms have different goals and cultures in their approach to research. For example, while scientists achieve recognition through making their findings well known in the research community (Dasgupta et al., 1962), industrial firms maintain competitive advantage by safeguarding technological knowledge from competitors (Frenken & van Oort, 2004). The need for exclusive rights to technological knowledge particularly applies during the commercialising phase; whilst other firms can also produce innovations, the ability to bring these technologies to the market is what enables firms to derive returns on investment. Therefore the closer a technology is to being commercialised, the higher the level of trust that is needed amongst actors. Boschma & Martin (2010) demonstrate that this need for trust requires greater spatial proximity between innovation and manufacturing.

However EEG also recognises that the spatial distance between innovation and manufacturing can increase once a technology 'matures'. Technological maturity occurs when the market for a particular technology picks a 'dominant design' – that with the greatest market acceptability (Cantwell, 1995). Interest in other product designs wane and the market switches its focus to reducing costs for the dominant design. One way to achieve this is by relocating production to economies with comparatively lower costs of production (Vernon, 1966). This shift can reduce, or even eliminate, the manufacturing of these particular technologies in the economies that originally innovated them (Ernst, 2006). However, it benefits economies with comparative advantage in low-cost production as it allows them to enter the industry through manufacturing (Wu & Mathews, 2012) and technology transfer processes enable them to increase their industrial capacity.

At this stage of technological maturity, actors can also reduce production costs through process innovations that improve efficiency. Many studies on East Asian economies demonstrate how process innovations occur during the actual manufacturing process (McDonald & Schrattenholzer, 2001; Watson et al., 2014). This learning-by-doing enables these actors to identify organisational improvements to routines and processes that are key to cost reductions. These economies leverage their access to manufacturing to increase their technological capabilities, which not only means an increase in production of more sophisticated technologies, but also engaging with more sophisticated innovation.

A good example of learning-by-doing can be seen in East Asian economies, notably South Korea, Taiwan, and China. These economies not only leverage their comparative advantage in manufacturing, but also undertake indigenous innovation. The increase in technological capabilities allows these economies to continuously 'absorb' external knowledge. However Hansen & Ockwell (2014) and Bell (2009) distinguish between technological capabilities and industrial capacity – with the latter referring to an economies ability to produce existing technologies. In contrast, technological capabilities include creating new product designs (i.e. product innovation) or even undertaking advanced engineering to improve the sophistication of production equipment. Dicken (2011) and Bailey & Bosworth (2014) recognise that production equipment is becoming highly automated, so process innovations for these technologies require more sophisticated innovation capabilities. These high level process innovations stand in contrast to lower levels of process innovations that occur through developing production capabilities (Hansen & Ockwell, 2014).

EEG recognises that when highly sophisticated engineering is required to improve production equipment, industrial firms will choose to undertake these process innovations near economies with technological capabilities. This is because the spatial embeddedness of innovation clusters attracts industrial actors to undertake joint research and development (R&D) for these technologies. Amin & Thrift (1992), Maskell & Malmberg (1999), and Storper (1997) argue that these 'centrifugal' forces reinforce these innovation clusters' importance within global production networks. These innovation clusters which have both innovative actors and industry can either can in Jacobian economies that have multiple industries located in a single cluster, or industrial districts that specialise in a given technology (Aoyama, Murphy, & Hanson, 2011). With regards to high level process innovations, it indicates that process innovation and industrial facilities are located within the same economy.

Economies that first innovated the dominant design can also continue to improve product design through iterative cycles. They can transfer these designs to production economies with the capabilities to retool their facilities to produce these designs. The idea of 'just-in-time' production first referred to Toyota's ability to produce new designs at a faster rate through innovations in production facilities (Monden, 2012), but has come to characterise East Asian economies that are part of global production networks (Dicken, 2011). These economies can quickly modify their production facilities to manufacture successive product innovations that are designed in foreign economies. Conversely innovative economies do not necessarily have to rely on the domestic industry to introduce updated designs of products that are already commercialised.

5.2.3 Considering economies without domestic industries

The focus of this chapter is to consider whether research institutes need access to domestic industry in the commercialisation process. Domestic industries are important for scaling production – which itself has systemic challenges. EEG also analyses how technological maturity influences the spatial distance between innovation and industrial actors. Studies on the innovation systems of industrialising economies highlight that economies with high production capabilities do not necessarily develop innovative capabilities.

However there is little literature on whether new product innovations –alternatives to the dominant design – require access to domestic industry for scaling and commercialisation. The literature derived from the systems failure and the EEG literature would hypothesise that these economies would need access to domestic industrial players. This is due to the importance of spatial proximity for enabling learning feedback loops and engendering trust.[6] Chapter 4 has identified economies who play an important role in solar PV research, but do

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[6]It should be noted that EEG recognises that scientists' networks are more openly collaborative with actors outside the economy, even for technologies that are at an early stage, because of the importance of creating knowledge spillovers through leveraging each other's specialisations. However This same literature finds a contrasting case with scientist-industrial partnerships. Industrial players invest in these ventures to obtain economic rent through proprietary ownership of the technology.

not have access to a large domestic industry (Carvalho, 2015a). How these researchers engage with foreign industrial partners – especially in comparison to researchers with access to domestic industrial partners – addresses an important gap in the literature.

Table 1. Comparative framework of opportunities and challenges to commercialise technologies, based on presence or absence of domestic industry

	Innovative actors located in economies with different industrial compositions	
Maturity of technology	**Presence of domestic industry**	**Absence of domestic industry**
Alternative technology (pre-commercialisation)	Presence of domestic industry provides opportunities for scaling production to commercialise technologies *(From the EEG literature).*	*(Hypothesis based on the current EEG literature)* Need for spatial proximity makes it challenging to commercialise alternative technologies with lack of domestic industry.
Dominant technology (commercialised technology)	Opportunities for high-level process innovations and improvements on product innovation with domestic industry. *(From the EEG literature).*	Linkages between these economies in technology transfer and joint R&D for process innovations *(From the EEG literature and innovation systems literature of industrialising economies).*

Based on: Bell, 2009; Boschma & Martin, 2010; Hansen & Ockwell, 2014; Maskell & Malmberg, 1999; Murmann, 2005; Storper, 1997

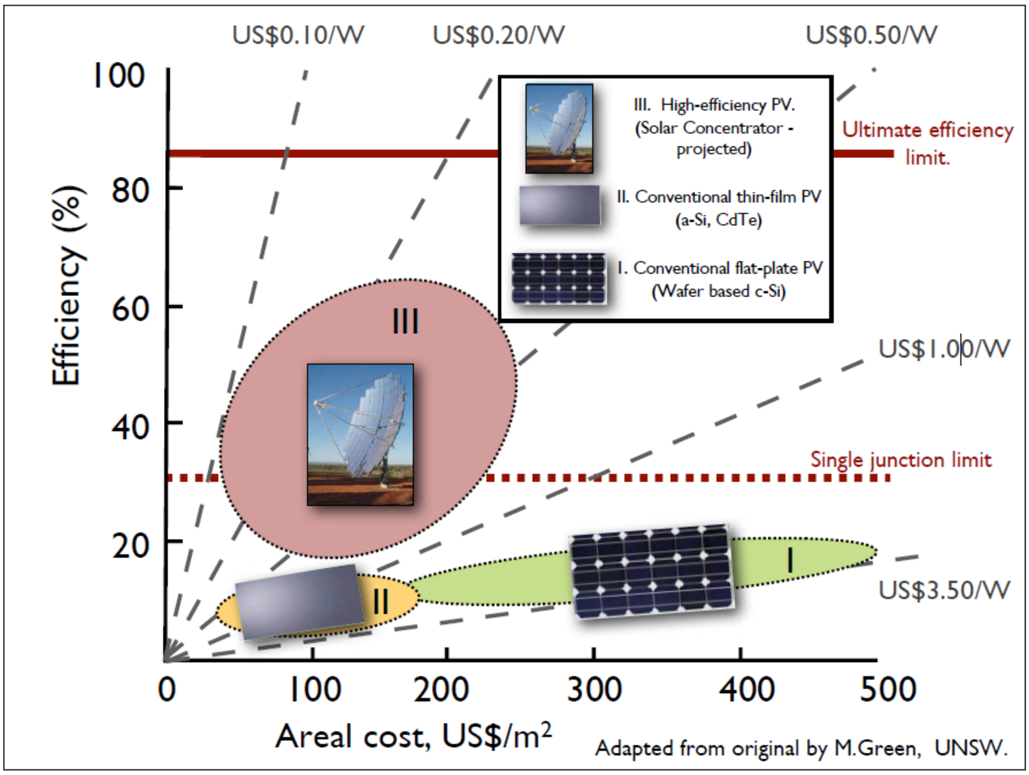
5.3 Solar PV technologies: case study and research methodology

5.3.1 Choice of the solar PV industry as a case study

Using the solar PV industry as a case study is useful as it has multiple product innovations at different stages of development. Solar PV technologies refer to the direct conversion of photon energy (derived from sunlight) into electricity through the use of semi-conductive materials (Green et al., 2015). PV cells are the main technological components that undertake the electricity conversion, and are made from different semi-conductive materials. The 'dominant' semi-conductive material is crystalline silicon. Alternative solar PV technologies either rely less on silicon materials, are derived from alternative semi-conductive materials (Chopra, Paulson & Dutta, 2004), or use a combination of semi-conductive materials (including crystalline PV).

The attraction of alternative technologies is that they have the potential to be produced at a lower areal cost (i.e. surface area) and/or higher efficiencies than crystalline PV, and have greater opportunities for different applications (Green, 2007; Hegedus, 2006). Figure 2 demonstrates how crystalline silicon PV (shortened to crystalline PV) has a higher areal cost than alternative PV technologies – as can be seen by their placement on the x-axis. For conventional thin-film PV technologies (denoted as II technologies in Figure 2), the amount of semi-conductive materials used is less – thereby being comparatively cheaper to crystalline PV for each square metre. However they also conduct less electricity from their exposure to sunlight (represented by the power efficiency levels on the y-axis). High-efficiency PV technologies (denoted as III technologies in Figure 2) can also be cheaper per square metre by being made of semi-conductive materials that conduct more electricity over the same surface area; or concentrating the focus of solar energy onto a smaller areal surface to conduct more electricity. In summary, areal costs of alternative PV technologies can be lower than crystalline PV technologies due to: (1) cheaper material inputs; or (2) having PV cells with higher power efficiencies. An additional attraction of thin-film and organic PV cells is their flexibility and integration with different materials, enabling alternative PV technologies to be incorporated into buildings, thereby increasing opportunities for architectural design and energy.

Figure 2. Areal costs and efficiencies for different solar PV technologies



Source: Ekins-Daukes, N.J., 2013, p. 10
Note: Conventional flat-plate PV (I) refers to crystalline PV technologies that have a maximum power efficiency limit of 32.7%. Conventional thin-film PV (II) has cheaper material costs, whilst high efficiency PV concentrator (III) can reach higher efficiencies.

Solar PV is particularly useful for this study as the production equipment of crystalline PV would not be suitable for alternative PV technologies (Green, 2007). The spatial implication is that an economy that produces crystalline PV technologies does not have an automatic advantage in developing alternative PV technologies. Instead, up-scaling the production of alternative technologies requires complementary knowledge from other industries. For example, many alternative technologies (such as thin-film and organic PV) require the production of large sheets of high quality material and can draw on experience from complementary production lines including glass, steel and photography (for the printing of film). These production facilities (or fabrication lines) can be used for upscaling based on existing processes and retooling for semi-conductive PV cell materials. Access to production technologies is important for overcoming two main challenges of commercialising technologies. The first is to achieve material quality in terms of durability and power efficiencies, as well as managing the toxicity of certain materials. The second is the scaling of production. This highlights the importance of industrial actors that in providing access to production technologies and facilitating learning-by-doing (Goodrich et al., 2011).

Crystalline PV technologies achieved early commercialisation due to knowledge complementarity with the semi-conductor industry for electronics, whose production equipment could be easily adapted. These knowledge complementarities enabled the USA, Japan, Germany and Switzerland's semi-conductor industries to retool fabrication lines for crystalline PV. This production equipment could then be sold to foreign economies – particularly to Chinese companies. With a number of Chinese firms taking up production, China's aggregate supply of crystalline PV grew from 255MW/year in 2005 to over 38,000MW/year in 2012 (Chase, 2013).

5.3.2 Methodology

The solar PV industry is a suitable case for the purposes of this study because it currently has a dominant and 'mature' technology in the form of crystalline PV technologies, as well as alternative PV technologies that are being developed from a different set of production tools. This research has identified actors that engage with innovation and commercialisation processes for both types of technologies, some of whom are located in economies with a domestic industry, some of whom are not. Using interviews as a research method was beneficial as interviewees were willing to talk about the nature and geography of their research-industrial interactions, some of which are confidential and would not necessarily be revealed on websites or public reports. Where available, this chapter used additional sources to corroborate the information on research-industry partnerships (e.g. company or research institute reports, or third party information).

This chapter takes a comparative approach in determining how access to domestic industries and the maturity of technologies shape the nature of research-industry partnerships. Qualitative, semi-structured interviews were conducted with innovative actors that fit within the cross-section of these categories. The interviews were semi-structured and purposefully open-ended to avoid biasing interviewee's responses. Nevertheless each interview addressed four thematic questions:

1. What kind of technologies is the interviewee involved in?
2. How does the interviewee engage with commercialisation efforts for these technologies?

3. (Depending on if the interviewee is part of a research institute or industry) How does the respective organisation engage with external actors in undertaking scientific research and/or industrial research? Where are external actors located?
4. How has the competitive dynamics in research – and the broader solar PV industry – affected the affiliated institute's research efforts?

A total of fourteen in-person interviews were taken with high-level and/or experienced actors in the solar PV industry. Another interview was undertaken via email exchanges. Each interviewee was chosen due to their seniority and extensive experience in the research institute and/or firm. Due to the sensitivity of certain views provided, the researcher took specific precautions in protecting interviewees' identity. This prerogative is especially justified in cases where actors can be identified from the cross-section of their knowledge specialisations and geographical affiliation.[7] Therefore, this research abstracted from geography and knowledge specialisations (revealed in Table 2 below).

The organisations studied for this chapter include research institutes, production equipment manufacturers, and final product firms located in Australia, China, Germany, Netherlands, Switzerland, UK, and the USA. These innovative actors are affiliated with the following solar PV technologies: crystalline PV, thin-film, polymers, and multi-junction cells. The technologies are at various stages of commercialisation. Pre-commercialisation refers to attempts to scale production before bringing the final PV product to the market. Early commercialisation refers to efforts in selling final PV products to the market. Commercialised technologies refer to final PV products that have already been sold to external buyers in the market.

Domestic industry access, shown in the last column of Table 2, refers to the presence of domestic industries with *complementary* knowledge in manufacturing that material, as well as whether the domestic industry produces crystalline PV. Table 2 thus reveals the categories that these actors fulfil and the kinds of partnerships they undertook. There is more than one interviewee (from different countries) that fall within each category. So although the sample size is small, the depth of the interviews with senior personnel still provides valid insights.

[7]The 'closed' nature of the solar PV industry makes it possible for those familiar with the industry to identify interview participants.

Additionally, the main findings of this research were derived from more than one interviewee – thereby providing some level of robustness. These insights reveal how access to domestic industry has influenced participants' commercialisation efforts.

Table 2. Summarised findings of industrial partnerships with different interviewees

Particip-ant #	Organisational affiliation (s)	Technology type	Commercial status	Type of partner (geography)	Domestic industry access?
P1*	University (Government funds research)	Organic and dye-sensitised PV	Pre-commercial	(1) Foreign research partners	(1) Large presence of domestic industry for crystalline PV (final products); (2) no domestic industry with complementary knowledge base in alternative PV technologies
P2	University (Government funding and Industrial Partnerships)	Organic and dye-sensitised PV	Pre-commercial	(1) Foreign industrial partner to use production equipment to up-scale technology; (2) Domestic and foreign research partners	Potential for domestic industrial base (presence of complementary industries)
P3	(1) Research institute (for PhD); (2) Career mostly in technology firms, appealing to private capital markets	Thin-film technology	Early stage commercial-isation	(1)Domestic industrial partner with complementary knowledge; (2) Worked on foreign technology transfers for government-led research partnerships	(1) Domestic manufacturing for crystalline PV;(2) Domestic industrial base with complementary technology for equipment manufacturing for semi-conductor and alternative PV technologies

Particip-ant #	Organisational affiliation (s)	Technology type	Commercial status	Type of partner (geography)	Domestic industry access?
P4	Solar PV firm	Thin-film technology	Commercialised technologies	(1) In-house R&D; (2) Technology acquisition of other alternative PV firms	(1) Domestic manufacturing for crystalline PV;(2) Domestic industrial base with complementary technology for equipment manufacturing for semi-conductor and alternative PV technologies
P5	Research institute (government and industrial partnerships)	Crystalline PV; multi-junction PV cells	Crystalline PV (commercialise; multi-junction (pre-commercial)	Foreign industrial partners	No domestic industry
P6[†,**]	Research institute (primarily industrial partnerships/ technology licensing; government funding)	(1) crystalline PV (commercialised); (2) thin-film (pre-commercialised)	Crystalline PV (commercialised); thin-film (pre-commercialised)	(1) Foreign industrial partners with crystalline PV technologies: technology licensing of PV applications and joint R&D of higher efficiency cells; (2) Domestic research partners for thin-film technologies	Domestic industry for semi-conductors and crystalline PV fabrication lines
P7	Research institute (government funding with strong emphasis on industrial partnerships)	Crystalline PV technology	Commercialised technologies	Mostly partnering with domestic industry for equipment manufacturing	Domestic industry for semi-conductor and equipment manufacturing for crystalline PV

Particip-ant #	Organisational affiliation (s)	Technology type	Commercial status	Type of partner (geography)	Domestic industry access?
P8	Research institute (majority of funding is non-government, with particular emphasis on industrial partnerships	Mostly crystalline PV	Commercialised technologies	Domestic and foreign industrial partners for improving production equipment	(1) Large presence of domestic industry for crystalline PV (final products); (2) no domestic industry with complementary knowledge base in alternative PV technologies
P9	Research institute (government funding with emphasis on industrial partnerships)	Crystalline PV technology	Commercialised technologies	Working with foreign research institutes and industrial partners to import technologies and cater to local market	(1) Large presence of domestic industry for crystalline PV (final products); (2) no domestic industry with complementary knowledge base in alternative PV technologies
P10	Solar PV technology firm	Crystalline PV technology	Commercialised technologies	Firm did in-house R&D and partnered with foreign research institute for joint R&D applications	(1) Large presence of domestic industry for crystalline PV (final products); (2) no domestic industry with complementary knowledge base in alternative PV technologies

Particip-ant #	Organisational affiliation (s)	Technology type	Commercial status	Type of partner (geography)	Domestic industry access?
P11	Solar PV firm (for upstream products)	Provide silicon wafers for crystalline PV and semi-conductor industry (commercialised)	Commercialised technologies	(1) Mostly in-house R&D; (2) Domestic and foreign research partnerships	(1) Domestic manufacturing for crystalline PV;(2) Domestic industrial base with complementary technology for equipment manufacturing for semi-conductor and alternative PV technologies
P12†	Industrial firm (conglomerate)	Equipment manufacturer and balance-of-systems	Commercialised technologies	(1) In-house R&D with affiliates around the world (mostly in domestic HQ); (2) most high-level innovations in country HQ	Domestic industry for semi-conductor and equipment manufacturing for crystalline PV
P13‡	Industrial firm (conglomerate)	Equipment manufacturer	Commercialised technologies	(1) In-house R&D with subsidiaries around the world; (2) Acquisition of domestic and foreign firms for technologies to improve production process; (3) Research partners with universities (based on specialty or technology transfer)	(1) Domestic manufacturing for crystalline PV;(2) Domestic industrial base with complementary technology for equipment manufacturing for semi-conductor and alternative PV technologies

Particip-ant #	Organisational affiliation (s)	Technology type	Commercial status	Type of partner (geography)	Domestic industry access?
P14‡	Industrial firm (conglomerate)	Equipment manufacturer	Commercialised technologies	(1) In-house R&D with subsidiaries around the world; (2) Research partners with universities (based on specialty or technology transfer)	(1) Domestic manufacturing for crystalline PV;(2) Domestic industrial base with complementary technology for equipment manufacturing for semi-conductor and alternative PV technologies
P15**	Industrial firm (solar PV)	Equipment manufacturer	Commercialised technologies	(1) Technology transfer processes to foreign countries (where customers are located)	Domestic industry for semi-conductors and crystalline PV production equipment

**Responded through email to in-depth questionnaire.*
***Located in the same country that has small industrial base for production equipment for crystalline PV.*
†*Interviewed two people from same organisation at the same time.*
‡*Belong to same company but based in different countries.*

5.4 Research findings & discussion

How does the nature of research-industrial partnerships differ when these actors have access to domestic industry? This chapter presents novel findings that explore the propensity and nature of research-industrial partnerships based on the presence (or absence) of domestic industries. For alternative technologies, it demonstrates that the openness to collaborate with industrial partners is based on the complementarity of knowledge; there is a greater willingness to work with foreign partners if the research institute's prototype can be up-scaled in the firm's facility.

In contrast, the presence (or absence) of a domestic industry that provides crystalline PV production equipment influences research institute's propensity to collaborate with actors in low-cost countries such as China. Research institutes that collaborate with domestic industrial partners limit research partnerships with Chinese firms (based on P7 and P8 responses). Instead, they recognise their role in helping domestic equipment manufacturers improve high-level process innovations that can then be sold to Chinese crystalline PV factories. However, the research institutes that do not have large domestic equipment manufacturers do engage with Chinese solar PV firms (based on P5 and P6 responses). The following sub-sections illustrate these dynamics.

5.4.1 Alternative PV technologies: The search for the right partner

The up-scaling of production for alternative PV technologies requires access to industrial production facilities that can be retooled to suit alternative PV purposes. Interviewees for alternative PV technologies reported that even when the PV cell was not yet ready for up-scaling, having an industrial partner was important in getting access to materials and production lines for learning-by-doing processes (based on P1, P2, and P3 responses). They acknowledged that finding the appropriate research and/or industrial partner is an important part of this learning process.

For interviewees that undertook commercialisation processes for alternative technologies, a major reason they could up-scale production was because the domestic industry had the appropriate production equipment. First Solar's first manufacturing plant was in Perrysberg, Ohio. Perrysburg is known for having a strong glass-making industry, which also benefits from industrial linkages with Ohio State University. Although First Solar manufactured this technology in-house, it chose to locate in Perrysburg due to the knowledge spillovers in glass making that occur within this industrial district. Another interviewee that undertook commercialisation of a thin-film technology said he partnered with an entrepreneur with connections in the optics industry. These findings reinforce the hypothesis that economies with a *diverse* set of industries have a higher probability of matching research and industrial partners for commercialising technologies. However, it does not guarantee that the match will enable technological commercialisation. One interviewee (P3) based in the USA highlighted the difficulties in finding the right partner due to financing issues, lack of experience in developing these technologies, and lack of a large-scale domestic PV market.

On the other hand, the *lack* of diversity in the domestic economy does not necessarily hamper the learning efforts of research institutes involved in alternative PV technologies. Social networks are an important avenue in internationalising research-industrial partnerships, especially as students and colleagues move into industries while maintaining ties with former research affiliations, including facilitating partnerships (based on P2, P3, P5, P6, and P8 responses). These interviewees highlight how the number of international research collaborations has increased with the professionalisation of the sciences (Beaver & Rosen, 1978), which refers to how a research community develops around a scientific subject – in this case, solar PV technologies. The nature of scientific research and funding – which focuses on novel contributions – also has specific knowledge specialisations developed in distinct geographies (Martin & Sunley, 2007). These geographies spatially cluster innovative actors involved within specific niches of solar PV technologies. All the interviewees recognised the specialities of different innovation clusters based on results published in prominent academic and industrial journals.[8] Furthermore, the interviewees highlight the importance of conferences in not only announcing new scientific findings (or improved results), but finding potential research/industry partners.

International recognition of research institutes' advances is an important factor in attracting scientific and industrial funding – even from foreign partners. All the interviewees that undertook alternative PV research were open to collaborations with foreign actors where

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[8]Prominent solar PV journals that interviewees frequently used for announcing results were the Journal of Progress in Photovoltaics: Research and Applications, the I EEE Journal of Photovoltaics, and Solar Energy Materials & Solar Cells.

there were benefits from leveraging each other's specialisations. Two of the interviewees who undertook alternative research said foreign industrial firms with complementary production facilities have approached them (based on P1 and P2 responses). These firms had made contact due to the prominence of these researchers' work in that field. Both researchers said that it was not necessary for the research institute and the manufacturing line to be in the same country in order for learning to take place.

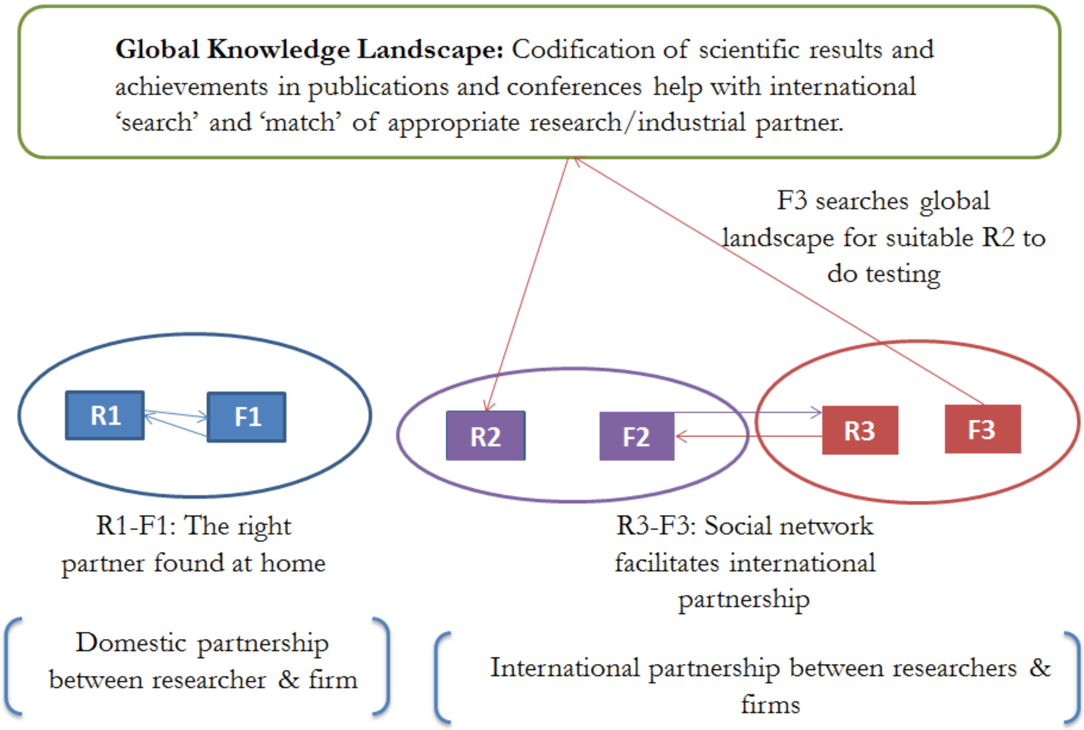
> [P1, organic and dye-sensitised PV researcher] *"I don't think being close is so important for OPV [organic photovoltaics] commercialisation. In fact, R&D sites can be far away from manufacturing sites. For example, I do have close collaboration with research partners in Europe or North America. Long distance is a very limited factors."*

> [P2, organic and dye-sensitised PV researcher] "*One common interest* [between solar cell researchers and photocopier manufacturers] is *we want to understand how fast the charges move in the material. They found a way of processing materials that they think will enable the charges to move faster. We've got the ability to do measurements and also the ability to do calculations. We have now a collaboration which involves we sending them pieces of glass. They would coat them with their materials and send them back and then we do the measurements and hope to come out with a publication together."*

These comparative findings draw two important conclusions. First, diversity in the industrial composition of the economy can enable knowledge spillovers in the *local* economy. This diversity in manufacturing can increase the opportunities to find a domestic industrial partner to commercialise alternative technologies. Economies that produce the incumbent technology (in this case, crystalline PV) cannot replicate the production lines of alternative technologies due to the lack of complementarity. This suggests greater resilience in economies that can commercialise alternative technologies.

Second, the lack of industrial diversity does not necessarily stop the research institute's pursuit of alternative technologies. Instead the professionalisation of alternative PV research can help both researchers and industries identify appropriate partners outside of the domestic economy. Therefore the lack of a domestic industry does not inhibit opportunities for learning-by-doing. Instead it enables international knowledge spillovers between research institutes and industries. Figure 3 presents a summary of how national and international partnerships can be formed between research institutes and industrial firms.

Figure 3. Different geographical avenues in creating domestic and international partnerships between research institutes and industrial firms



Source: Author schematic

5.4.2 Commercialised technologies: How presence (or absence) of domestic industries affects motivations for industrial partnerships

The successful commercialisation of crystalline PV products depends on producers' ability to compete by: (1) increasing power efficiencies of PV cells; and/or (2) improving production efficiencies to decrease production costs (van der Zwaan & Rabl, 2003). Both cases require high-level process innovations to improve production equipment. For crystalline PV innovation, spatial relationships between research institutes and PV equipment manufacturers are particularly important. Interviews conducted for this study reveal how the presence or absence of domestic industry impacts the propensity to partner with industrial partners, as well as the nature of that partnership (please refer to summary in Table 3).

This research interviewed four research institutes (P5, P6, P7, and P8) in the study that were outside of China, and were involved in crystalline PV research. The novelty of this research lies in understanding which research institutes partner with Chinese solar PV firms. There is a focus on China because it has the largest share of manufacturing of final solar PV products (BNEF, 2012). This means that Chinese solar PV firms are potential customers for importing production equipment but also competitors to other final PV producing firms. It was revealed that the presence (or absence) of a domestic industry that *sells* technologies to Chinese customers influences the propensity to partner with Chinese solar PV firms. It should be noted that interviewees based in China highlighted the importance of collaborating with foreign research partners to undertake technology transfer and joint research collaborations. These findings corroborate the expectation that late-comers continue to rely on foreign partners (or innovation centres) to build both production and innovation capabilities(Ernst, 2009; Fu & Gong, 2011; Fu & Zhang, 2011; Peidong et al., 2009).

The two research institutes (P7 and P8) that had domestic industry (in the form of semi-conductor technologies) both admitted that they had limited – or even refused – partnership offers from Chinese PV firms, while accepting funding from other foreign industries (in addition to domestic firms). The aversion to partnering with Chinese solar PV firms was due to domestic industry considerations. First, these research institutes depended on domestic industrial partners to engage in learning feedback loops for undertaking high-level process innovations, as well as industrial funding. They therefore did not want to undermine the economic opportunities of domestic equipment manufacturers selling to Chinese companies. Furthermore, they wanted to ensure that knowledge spillovers continued to benefit the domestic industry, since they were the only avenue for remaining competitive with low-cost producers. These interviewees highlighted that cultural and language differences acted as barriers to partnerships, but that the resilience of domestic firms was the most important factor in limiting research collaborations.

> [P8, Crystalline PV Researcher] *"[…]because of the competition between the [domestic country] solar industry and the Chinese, we are not directly going to China because this would be complicated. First of all we would like to support the [domestic country] industry,* [especially as] *there's strong competition* [between the domestic industry and China]. *On the other hand, a lot of the equipment makers here in [domestic country] are selling directly to China, so there's an indirect contact with Asia and China…"*

[P8, Crystalline PV Researcher] *"*[…] *We have no direct projects with Chinese companies, but, because we are cooperating with solar cell companies here* […] *we really want to see that they have a chance to survive* […]*"*

[P7, Crystalline PV Researcher] *"You can innovate in Europe and get it transferred quickly to China. In our case, especially for the very new things development that has a high potential, if we work for instance with equipment makers, we will not directly collaborate with the company in China. We really want, and first Europe to be able to get something out of the technology. Then it is up to the equipment maker to have a close collaboration with the end user of the equipment.*

In contrast, the two research institutes that did not have a large domestic semi-conductor or crystalline PV industry did have strong industrial partnerships with Chinese companies. The first research institute is the Australian Centre for Advanced Photovoltaics at the University of New South Wales (UNSW). The second institute is the Energy research Centre of the Netherlands (ECN). These research institutes benefitted from early government funding for developing high efficiency crystalline PV cells. However, as government funding has waned, and with insufficient domestic industry to provide financial resources, both research institutes have had to rely on engaging with foreign industrial partners.

It should be noted that these research institutes had differing approaches to developing industrial partnerships with Chinese companies. ECN approaches Chinese firms as potential customers for their research services (i.e. offering business-to-business [B2B] services). More specifically, it engages with Chinese firms to sell technology licences and undertake research consultancies and joint R&D. Since China is the largest manufacturer in the world, it is also the largest market for ECN services. With regards to enabling certain product innovations, ECN was successful in a joint venture to scale an n-type silicon with Yingli (a Chinese PV company) and Tempress (a Dutch equipment manufacturing company) (ECN, 2012, p. 14). It also successfully developed a world record-holding PV module[9] with two Chinese crystalline PV companies[10] and two other firms. It should be noted that ECN did not partner with Chinese firms for the purpose of scaling alternative PV technologies. Instead ECN used

[9]This is for rear contact modules.

[10]CSI and JA Solar

their knowledge specialisations in crystalline PV as an opportunity to 'export' research consulting and R&D services to foreign firms interested in contracting their research.

UNSW also has strong industrial partnerships with Chinese solar PV firms due to its social network. Many Chinese solar PV scientists studied at UNSW and returned to China to undertake entrepreneurial ventures. The most well-known Chinese alumnus is Shi Zhengrong, the founder of Suntech – once one of the world's largest solar PV companies. A prominent crystalline PV researcher from UNSW, Dr Stuart Wenham, also serves as the Chief Technology Officer for Suntech. However, many Chinese scientists from UNSW went on to start, or be part of management teams for, 'tier 1' crystalline PV companies in China. These social networks facilitated interpersonal trust and student-industry exchanges between UNSW and these companies. UNSW is an important educational centre for training solar PV scientists, recognised globally for its advances in crystalline PV technologies. It attracts leading solar PV scientists and firms to undertake collaborations and can leverage these networks to attract additional partners. In response to a query about the importance of a leading American scientist joining the Centre's research team, the participant [P5] said:

> [P5] *"His contacts to the US are very valuable to us. He brings in people that he used to work with from the University of Delaware. The contacts he's retained, knowledge and access on who to talk to is a big head start. He can approach them with credibility, because they know who he is, and he's not sort of cold calling them. He's brought in a lot of US partners that we might not have had access to otherwise without a whole lot harder work."*

These findings provide important insights into how the presence (or absence) of domestic industries that cater to mature technologies affects international research-industrial partnerships. For the two research institutes with domestic production equipment manufacturers, the reticence to partner with China was unrelated to spatial distance. Their refusal was more techno-nationalistic – ensuring that their role in providing knowledge spillovers benefited the domestic industry. These industrial players in turn could provide value to the domestic economy by exporting these high-value technologies. In contrast, the lack of a domestic industry obviated these techno-national considerations for UNSW and ECN. Instead, Chinese foreign partnerships fulfilled the necessary investment to support the R&D activities of these institutes. Whilst ECN focused on exporting research services and providing temporary exclusive licensing of technologies to firms, UNSW recently undertook an 'open innovation strategy'.

> [P5] *"Our university's actually taken a different line, more recently, and where a lot of our technologies are freely available. Just work with us, and we'll do research together."*

Table 3. Summary of findings: Partnerships between research institutes and industrial firms

Maturity of technology	Innovative actors located in economies with different industrial compositions	
	Presence of domestic solar PV industry, including equipment manufacturing industry	**Absence of domestic industry (or small-scale domestic industry)**
Alternative technology	Presence of existing crystalline PV technologies is not suitable for alternative technologies. Commercialising alternative technologies is dependent on knowledge complementarities between research institutes and industries. Domestic economy more likely to benefit from commercialisation if it has a diverse set of domestic industries.	The absence of domestic research and/or industry with knowledge complementarities does not limit industrial partnerships. The professionalisation of sciences (in terms of getting recognition for work) can facilitate international collaborations between research institutes and industries to engage in experimental learning and scaling efforts.
Crystalline PV technology	Limited partnerships between research institutes and industries in countries with low-cost manufacturing of crystalline PV technologies. Recognise the importance of using knowledge spillovers to enhance competitiveness –and export opportunities – of domestic industry.	To capitalise on the 'embeddedness' of research capabilities in crystalline PV, institutes partner with foreign companies interested in technology transfer and improving innovation capabilities. These partnerships can occur through B2B research services, and/or social networks.

Source: Author's compilation.

5.5 Conclusion. Implications for current and future research

This chapter has explored the implications of access to domestic industry for the commercialisation of solar PV technologies. The findings are also potentially applicable to other industries with similar diversity in alternative technologies. However, it acknowledges that these research findings are preliminary and that a broader sample of actors representing the different cross sections need to be surveyed in order to make these comparisons more generalisable and robust. Nevertheless these initial findings are novel, and are validated by at least two independent sources from each category. This comparative approach provides essential nuances to the spatial relationship between innovation and manufacturing.

EEG emphasises the importance of spatial proximity between scientists and engineers when engaging in early-stage innovation (Audretsch & Feldman, 1996). When research collaborations between these actors are international, shared language and culture, as well as social networks are important for overcoming spatial distance (Boschma & Martin, 2010). This mode of networking creates 'supra-regional' connections, as opposed to the global innovation network (Luukkonen, Persson & Sivertsen, 1992; Ponds et al., 2007). This research confirms that shared languages and social networks can overcome 'spatial distance' in facilitating these collaborations, however it also emphasises how the professionalisation of the sciences creates a 'global knowledge landscape'[11] that identifies research institutes (and even firms) with more unique technological niches (Verbong & Geels, 2007). These findings suggest that spatial proximity is a beneficial, but not necessary, condition for early-stage commercialisation efforts.

This chapter also recognises that the presence of a large crystalline PV industry within an economy does not predict the likelihood of developing the next set of product innovations. In fact it corroborates Boschma & Martin's (2010) observation that close linkages between research institutes and firms (in this case, domestic equipment manufacturers) creates a path dependency. Nonetheless much of the EEG literature recognises how innovation clusters attract linkages with multiple economies involved in complementary industrial activities, creating global innovation networks (Maskell & Malmberg, 1999; Storper, 1997). For mature technologies, there are even greater linkages between innovation hubs and manufacturing centres (Ernst, 2009). However this research identifies a new factor that can influence these linkages: how the level of interactivity between domestic research institutes and industries can raise political economy considerations in collaborating with foreign partners. Research institutes can intentionally choose not to work with foreign industrial partners if it threatens the competitiveness of the domestic industry. In contrast, the absence of a domestic industry does not obstruct the research efforts of globally recognised innovation clusters. Instead, these innovative actors are more willing to engage in foreign research partnerships – particularly with countries that do not have comparative advantage in research. In other words, social and economic linkages between research institutes and domestic industry can limit or facilitate international spillovers.

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[11]Global knowledge landscapes differ subtly from global innovation networks in that they don't rely on formal or informal networks between innovative actors, but rather that actors can use globally available codified knowledge to search for the right partner.

These findings highlight the disjuncture between technological races and green growth. A country can win a technological race making a technological breakthrough or being the first to commercialise the technology (Atkinson et al., 2009; Fankhauser et al., 2013; Pew, 2013). There is then a techno-national expectation that the domestic economy will have a competitive advantage in selling these technologies to domestic and global markets, leading to green growth. However this chapter belies the assumption that a single country will win the race, as efforts to commercialise early-stage technologies can occur through international collaborations by matching research and industrial actors through knowledge complementarities. Although a country with a diverse industrial composition is more likely to commercialise technologies, linkages are not guaranteed unless research institutes and industries cooperate with one another. This chapter also recognises that economies that have developed these linkages between research institutes and industry can reap green growth in the long run by engaging with high-level process innovations. Nevertheless, innovative countries without these domestic linkages can still export research services to foreign industries. These linkages demonstrate that the race for green technologies and the realisation of green growth can be won through international cooperation.

5.6 References

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Chapter 6: Thesis conclusion. Reflections on thesis contributions to the literature on green growth and evolutionary economic geography

Examining the importance of a spatial perspective on technologies and industrial activities

6.1 Introduction

This thesis focused on two aims in evaluating the emerging literature on green growth. The first aim of this thesis was to identify a key gap in the current literature on green growth and the competitiveness of economies. As both developed and emerging economies invest into green industries, the 'race' for green technologies implies that domestic economies' opportunities to realise 'green growth' is threatened by global competition (Barua, Tawney, & Weischer, 2012; Dutz & Sharma, 2012). The current literature addresses this issue by evaluating the success of environmental policy instruments in stimulating green innovation (Ambec et al., 2013; Dechezleprêtre & Sato, 2014; Lanoie et al., 2011). Another set of the literature compares how various economies develop national innovation systems for green technologies (Jacobsson & Karltorp, 2013; Kamp, Smits, & Andriesse, 2004; Verbong & Geels, 2007). Whilst these literatures are important in highlighting the significance of innovation, they lack a spatial understanding of how technologies mature beyond innovation – and its implications on *where* different industrial activities locate as a result of these dynamics.

Recognising this spatial perspective is important – not just in terms of redressing political economy concerns about the perceived loss of competitiveness when manufacturing shifts to low-cost economies. The second chapter developed a conceptual framework on how the spatial dynamics of various technologies influence where different industrial activities locate over time – thereby affecting the domestic economy's ability to realise green growth (Carvalho, 2015c). This framework integrated key theories from evolutionary economic geography (EEG) that could reconcile the tension between the spatialisation of technologies and localisation of green growth. These theories include the spatial product life cycle (PLC) – which demonstrates how spatial relationship between innovation and manufacturing activities separate once technologies mature (Audretsch & Feldman, 1996; Boschma & Frenken, 2006; Coe & Bunnell, 2003). The consequence of technological maturity highlights the importance of innovation in enabling first-mover economies to withstand these shifts in manufacturing by capitalising on their specialised knowledge in innovating to develop the next set of technologies, and/or engage in high-level process innovations (Christopherson, Michie, & Tyler, 2010; Pike, Dawley, & Tomaney, 2010). By recognising that manufacturing can be more prone to spatial shifts than innovation in the latter stage of the PLC, EEG demonstrates how economies can be resilient to global competition. Chapter 3 applies this framework to provide evidence of this spatial decoupling occurring in the global solar photovoltaic (PV) industry (Carvalho & Perkins, 2015).

Nevertheless EEG highlights how the spatial relationship between innovation and manufacturing does tend to be spatially proximate in the first stage of the PLC – that is, prior to the commercialisation of technologies (Etzkowitz & Leydesdorff, 2000; Khan & Park, 2011; Ponds, van Oort, & Frenken, 2007). Therefore the next two chapters of the thesis continued to use the solar PV as a case study to examine the spatial relationship between innovation and manufacturing. Through its empirical research on the solar photovoltaic (PV) industry, it investigated whether domestic economies needed both innovation and manufacturing in order to commercialise technologies. The cumulative findings of this research seek to provide a more nuanced understanding of whether economies pursuing technological innovation actually do need a spatially proximate relationship to enable learning spillovers. These findings contribute to a gap in the EEG and innovation systems failure literature – which assume innovative actors do have access to domestic industry when undertaking early commercialisation of technologies.

Through exploring these aims through four inter-related papers, this thesis summarises three important conceptual contributions to the literature on green growth and EEG. The first contribution is to the green growth literature – which focuses on how the spatial characteristics of technologies and industrial activities affect domestic economies' exposure to global competition in supplying green technologies. The second contribution provides a nuanced consideration of how an economy's access to domestic industry can affect who it collaborates with internationally. This contribution can advance the literature from EEG on the importance of spatial proximity between research and manufacturing prior to technological commercialisation. It also recognises how the presence (or absence) of a domestic industry can raise political economy factors that can affect whether domestic actors engage in research collaborations with foreign competitors. The last contribution of this thesis presents the argument that the green growth literature needs to rebalance its focus on competitiveness of green economies by also realising the economic growth opportunities from market expansion.

The next three sub-sections reflect on how the findings from the four chapters can be integrated to provide salience to these three contributions. Each section also considers how these preliminary findings can be further explored through additional research. The last section provides concluding remarks for the thesis.

6.2 The spatial characteristics of technologies and exposure to global competition

The current literature on the competitiveness of green economies focuses on how innovation will enable countries to achieve long-term competitive advantage in these industries (Fankhauser et al., 2013; Stern & Rydge, 2013). This thesis supports this assertion. But it also recognises that the concept of an industry can be deconstructed into innovation, manufacturing, and markets. Undertaking this deconstruction is important as it enables analysis on how these industrial activities have various spatial characteristics that affect where they are located – not just in terms of relative spatial distances to each other, but how these spatial distances can change over time due to the maturity of the technologies themselves (Bathelt & Glu, 2003).

Both Chapter 2 and Chapter 3 use EEG's concept of spatial product life cycles as a starting point in understanding that the spatial relationship between innovation and manufacturing is spatially proximate during the pre-commercialisation of technologies in order to enable learning feedback loops between these innovative actors (Carvalho & Perkins, 2015; Carvalho, 2015c). However once the knowledge underlying production is codified to be transferable, manufacturing can be shifted to increase the industrial capacity in 'late-comer' economies (Aoyama, Murphy, & Hanson, 2011). Unlike manufacturing though, EEG demonstrated that innovation tends to be more spatially embedded within the domestic economy as it relies on knowledge generation assets developed from through the national innovation system (Asheim & Isaksen, 2002; Storper, 1997). EEG concept of resilience highlights how economies that first commercialised these technologies can capitalise on their technological capabilities to engage with both product and process innovations for the next cycle of technologies (Boschma, 2004; Pike et al., 2010).

The preliminary findings from Chapter 3's comparison of the proportion of countries' contributions to both global research and manufacturing do highlight that spatial decoupling persists in industrial research (represented by patent and best-in class data) (Carvalho & Perkins, 2015). However there appears to be convergence between first-mover and late-comer countries – particularly China – in scientific research (represented by academic publications). Therefore these findings do recognise that late-comers such as China are increasing their research efforts in these technologies. However it is not discernible if these research efforts are successful in either product or high-level process innovations. Even countries such as South Korea, who do demonstrate high proportion of inventor and firm patent counts, only occupies the upstream part of the solar PV value chain that provides silicon material to the rest of the value chain.

The findings from Chapter 4 and Chapter 5 can also provide important nuances to the spatial relationship between innovation and manufacturing for each economy (Carvalho, 2015a, 2015b). Chapter 4 reveals that research collaborations for both scientific publications and patent datasets continue to be predominantly national (Carvalho, 2015a). Therefore regardless of where manufacturing occurs, it re-asserts EEG hypothesis of research networks being spatially clustered despite the absolute increases in international research collaborations. In looking at whether economies should have access to domestic industry for commercialising efforts of early-stage technologies, Chapter 5 highlights it is preferable but not a necessary condition for early-stage technologies (Carvalho, 2015b). Chapter 3 also identified countries with high research output but not a large domestic industry, whose role in innovation networks was analysed in subsequent chapters (Carvalho & Perkins, 2015). The findings with Australian and Dutch solar PV researchers do capitalise – or attract – research with countries that have high industrial capacities to engage with research (Carvalho, 2015b). This finding presents a potential contribution of this thesis to the EEG literature by highlighting how first-mover countries with no industrial capacity can still play a role in global innovation networks by collaborating with countries that do have industrial capacity – including late-comer economies. The novelty in this finding is considering how differences in industrial capacity create motivations for international research collaborations. Furthermore it shows the continued significance of these economies to global innovation networks.

Chapter 5 also reveals that the relevance of domestic industry to research efforts in scaling early-stage technologies is the level of knowledge complementarities between the types of actors (Carvalho, 2015b). It thus highlights that diversity in industrial composition can increase the probability of finding the right knowledge partner. Nevertheless if domestic industries are not interested in engaging with research institutes to commercialise these alternative technologies – the opportunity is missed by the local economy. However in these cases, research institutes can partner with willing foreign industrial partners – creating international knowledge spillovers. These findings can challenge the EEG literature's emphasis on the necessity of spatial proximity between scientific research and industries in either early-stage or mature technologies. This is assuming of course, that the right international partner exists to undertake this research.

6.3 The significance of domestic industrial capacity on the spatial relationship between innovation and manufacturing

Whilst the prior sections findings highlight whether having access to a domestic industry is necessary to for domestic scientists to engage with industrial research, the presence of a domestic industry can influence patterns of international collaborations. A surprising finding in Chapter 4 is that the observed/expected ratios – which enables ranking of the relevance of different partner countries to a particular country – demonstrate that countries that are within the top hierarchy of global innovation networks do not collaborate with each other as the literature would suggest (Carvalho, 2015a). For Germany, the countries that are most relevant to them are other European countries – reinforcing the importance of spatial proximity. However it is surprising that Japan, USA and China – who also has a high central position in the network in the latter time period – do not actually have each other within the most relevant countries. Instead these countries tend to collaborate with other countries that do have relatively high technological capabilities – but a smaller (if non-existent) domestic industrial capacity. This result is only preliminary, and more in-depth quantitative analyses on the datasets should be taken to reveal the robustness of this finding.

Chapter 5 actually does provide supportive evidence of this hypothesis, as it recognises how the domestic industrial capacity can raise political economy issues in engaging with collaborations with foreign economies (Carvalho, 2015b). The interviewees from research institutes that worked in close conjunction with domestic industries intentionally limited collaborations with Chinese partners. The purpose was to ensure that their knowledge spillovers benefited domestic industrial partners – who could then sell these proprietary technologies to foreign economies. However the absence of a domestic industrial partner removed this techno-national concern – and in many ways, encouraged seeking collaborations with foreign industrial partners. These findings contribute to the EEG literature by identifying how political economy factors can affect countries' propensity to undertake research collaborations with partners that can threaten competitiveness of domestic industry. However this factor appears to be prominent if there is actually close linkages between research institutes and industry. The findings from interviewees in the USA and UK – which both have domestic industries with knowledge complementarities – highlight that domestic industrial partners also need to be willing to undertake these collaborations.

The presence (or absence) of domestic industries reinforces EEG's importance of how innovation can provides growth opportunities for economies. For economies that do have close linkages between research institutes and firms, it enables knowledge spillovers that increase the technological capabilities of the domestic economy. In doing so, it enables domestic firms to sell high-value technologies to foreign economies that is difficult to replicate. However for economies that do not have domestic industry, research institutes can still find growth opportunities by 'exporting' their services to foreign economies interested in increasing their technological capabilities – as is the strategy of both Dutch research institutes and a small-scale industrial firm. Alternatively research institutes can attract participants through offering educational training, and open research collaborations – as a leading solar PV institute in Australia is undertaking. These findings are intriguing, but preliminary. Further interviews with different sets of research and industrial firm actors that are in economies with different levels of technological capabilities and industrial capacity are needed in order to increase the robustness of the findings.

6.4 Re-balancing green industrial policy to optimally realise green growth from supply and demand side activities

The last major contribution this thesis provides to the literature on green growth is to highlight how the spatial characteristics of technologies can affect whether the domestic economy can optimally realise growth from a balance between supply and demand-side activities. Chapter 2 develops a framework that demonstrates how the spatial mobility and replicability of technologies affects whether domestic economies can be resilient to global competition (Carvalho, 2015c). It highlights that economies can be resilient to global competition if: (1) no other economy can replicate these technologies; (2) the low spatial mobility of technologies means that needs to be manufactured in domestic markets. If the first condition occurs, then economies can sell these technologies to global markets. However if other economies can replicate these technologies, it does not necessarily mean they can access domestic markets if the technologies have high transport costs, or trade costs. Whilst high transport costs means that it is more cost-effective for manufacturing to be close to markets, trade costs can artificially impose these costs to favour domestic industries.

In looking at the solar PV industry, a post-reflection of the findings from Chapter 3 recognise the difference between the success of technological commercialisation versus growth opportunities for the economy. Technological commercialisation refers to when a technology is able to compete in the wider market. Liebreich (2013) reveals that the increase in the production volume of crystalline PV technologies from all the participants – but most particularly China – led to an 80% drop in global PV prices. The result was that solar PV technologies achieved grid parity in several markets – thus negating the need for subsidies. Whilst these depressed prices were beneficial for solar PV demand – firms from Europe, USA and China were either acquired or went bankrupt as they could not manufacture solar PV technologies below this market price. This finding reinforces the point that economies which only manufacture technologies that other economies can appropriate and replicate become less resilient.

Despite the reduced resilience in supplying green technologies, economies can still achieve green growth through demand-side activities. UNEP & BNEF (2013) demonstrates that global investments in demand-side activities (i.e. asset financing) far outweigh supply-side investments. Furthermore supporting the deployment of green technologies in domestic economy can yield a range of job opportunities that are more reliant on *domestic* labour. However in order to capitalise on these market opportunities, domestic policy-makers need to ensure that they are not unnecessarily swayed by techno-national concerns that seek to protect domestic industry. These concerns can be justified in creating strategic niche markets for the development of early stage technologies (Schot & Geels, 2008). Of course, this kind of market protection does not require protection from foreign competitors in supplying these technologies – but it is needed to create a protected learning space that is not undermined by incumbent technologies (Unruh, 2002; Verbong, Geels, & Raven, 2008). However it makes less sense to protect domestic industry – that potentially sacrifices market expansion – if these technologies are commercialised and the production is easily replicable in other countries. This protection especially seems unnecessary if technological firms in first-mover countries, such as USA, Germany and Switzerland, sold the production equipment to China to enable the latter's increase in industrial capacity (de la Tour, Glachant, & Ménière, 2011; Pew, 2013).

In considering these contributions, this thesis argues that both the academic literature and policy-makers need to understand the spatial characteristics of technologies in order to assess how economies can realise growth from either supply or demand-side activities. These spatial characteristics include: (1) understanding at what stage of commercialisation technologies are at, and its implications on either providing growth opportunities through supply (if few other economies can replicate) or demand (by getting access to cheaper technologies); (2) the transport costs that affect spatial mobility of technologies – determining whether market policies can still yield growth from manufacturing; and (3) the opportunity costs of trade to domestic markets (if technologies are replicable and have low costs of transport). Though this thesis largely relies on the solar PV industry as a case study, the spatial framework itself can be applied to different technologies – especially with regards to considering how the spatial 'distance' between the associated industrial activities will locate in relation to each other. These factors affect how different economies can realise green growth even with the internationalisation of green technologies.

6.5 References

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