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International Research Networks: Determinants of Country Embeddedness

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Abstract

We analyze the evolution of the international collaboration network in photovoltaic research. Using data on scientific publications for the period 1980–2015, we apply social network analysis to trace the evolution of the global network of countries and national research networks of organizations. Our objective is to identify the determinants of countries' international research embeddedness by looking at national policies and structural properties of the national research networks. We observe a steady increase of publications and collaboration within the global research network. While there is a small group of countries that remains central throughout all years, several countries emerge and catch up while others lose their relative position.We find that cohesion and connectedness of the national system positively affect research output as well as international embeddedness, whereas centralized systems are less embedded. Policy, especially demand side instruments, has a positive effect on publication output and embeddedness.

Keywords: International Collaboration; Research Network; Photovoltaics; Instrument Mix; Bibliographic Data

JEL Classification: L14, O31, O38, Q42

1 Introduction

The generation and diffusion of knowledge is an interactive process between a multitude of actors (Dosi, 1988; Powell et al., 1996). Connections to a diverse set of actors provide access to external knowledge which is considered crucial for own research, successful innovation, and eventually economic performance (Powell et al., 1999). However, access to external knowledge is not only dependent on direct collaboration partners, but also influenced by indirect linkages, or more generally, by the position in the knowledge network (Ahuja, 2000; Schilling and Phelps, 2007). Geography is a relevant aspect in the analysis of collaborations and networks. While connections to co-located actors might be more frequent and easier to establish, partners in distant locations in the form of international collaborations are considered highly fruitful (Cantner and Rake, 2014; Herstad et al., 2014). Regarding the determinants of tie formation and network positions, several theories have been developed in sociology, physics, management, or economics (for reviews see Ozman, 2009; Cantner and Graf, 2011; Phelps et al., 2012; Hidalgo, 2015). The decisions to form ties in knowledge networks are typically determined by individual characteristics, such as attractiveness in terms of capabilities, or by dyadic characteristics, such as geographical distance. These decisions are taken by individuals or organizations where international linkages connect different countries to form an international research network (Owen-Smith et al., 2002). Knowledge development is an increasingly global phenomenon, so that it is economically relevant for any country to be integrated in international research networks. Before this background, policy can create an environment conducive to international collaboration which might lead to a central position of the country within the international research network. Since the determinants of international research embeddedness are not well understood, we want to fill this gap and provide some novel perspectives on the analysis of international research networks.

We seek to identify the determinants of international embeddedness for the case of photovoltaic (PV) research. Given the rising awareness of climate change, research and development (R&D) in environmentally friendly technologies is increasing, even though R&D in this field faces several disadvantages (Rennings, 2000; Jaffe et al., 2005). Renewable energies and especially PV are generally seen as promising technologies to mitigate climate change. Since renewable energies have been – and still are – competing with existing technologies which produce electricity at lower costs, many governments decided to support the development of renewable energies by fostering R&D activities, providing investment subsidies, and/or promoting their diffusion (Jaffe et al., 2002; Kemp and Pontoglio, 2011; Groba and Breitschopf, 2013). While there is a growing literature evaluating the effect of policies on innovation and diffusion in PV (e.g. Watanabe et al., 2000; Johnstone et al., 2010; Peters et al., 2012; Wangler, 2013; Polzin et al., 2015; Cantner et al., 2016), there are hardly any studies dealing with the influence of different policy measures on scientific performance and the position in the international collaboration network.

We argue that the position of a country in the international research network is influenced by two driving forces. First, international embeddedness should be affected by the functionality of its innovation system (Nelson, 1993; Lundvall, 1992; Carlsson and Stankiewicz, 1991). We focus on one particular aspect of the innovation system, namely its interaction structure, which is highly relevant for knowledge diffusion within the system (Cowan and Jonard, 2004; Schilling and Phelps, 2007; Cantner and Graf, 2011; Herstad et al., 2014). This argument is related to the links between micro, meso, and macro levels of economic analysis (Dopfer et al., 2004). Here, the structure of the national networks, i.e. the functionality and the way the research system is set up, is a determinant of international collaboration behavior. In the empirical analysis of this relationship, we exploit the multimodal structure in publication data and link the national research network structure to the position of a country in the international research network. We expect that different national strategies concerning its openness, connectedness, and centralization should more or less conducive to international collaboration. Second, since a great share of research is publicly financed, countries' embeddedness is influenced by their policies towards PV. The strategies towards PV differ sufficiently between countries in terms of activities and timing which enables us to identify their impact on international embeddedness. A recently emerging literature on the policy mix convincingly shows the relevance of various dimensions of policy making (Flanagan et al., 2011; Rogge and Reichardt, 2016). In this paper, we focus on the instrument mix, covering direct R&D funding, demand pull instruments, but also a general commitment to tackle climate change by the ratification of the Kyoto Protocol. Furthermore, we extend this common set of policy variables by accounting for public procurement (proxied by the cumulative number of satellites), which is especially relevant for research activities in early phases of technology development (Geroski, 1990; Edler and Georghiou, 2007; Aschhoff and Sofka, 2009; Guerzoni and Raiteri, 2015). We test the effect of the national network structure and policy interventions on the embeddedness by OLS panel regression for the periods from 1980 until 2015.

We observe a steady increase of publications and collaboration within the global research network. While there is a small group of countries that remains central throughout all years, there are some countries catching up while others lose their relative position. We find that cohesion and connectedness of the national system positively affect research output as well as international embeddedness, whereas centralized systems are less embedded. Policy, especially demand side instruments, have a positive effect on embeddedness.

The paper proceeds as follows. We review the literature and derive hypotheses in Section 2. In Section 3, we first describe the publication data and then the international as well as the national collaboration networks. In part 4, we present the econometric study where we estimate the effects of the national network structure and different policies on the embeddedness of countries. Our results are discussed in Section 5, Section 6 concludes.

2 Literature review and research objectives

2.1 Networks of scientific collaboration

Knowledge generation is an interactive process in which the relationship between actors is key for knowledge exchange and diffusion (Dosi, 1988; Powell et al., 1996; Ahuja, 2000). During the last decades, collaboration in research has steadily increased and it has been shown to lead to more valuable output than individual research (Adams et al., 2005; Wuchty et al., 2007; Adams, 2013). Increasing specialization and division of labor leads to larger teams and competence building and sharing. However, researchers who collaborate, as documented e.g. by co-authorship, do not just add their individual expertise for a joint output but also exchange information and learn from each other (Breschi and Lissoni, 2004). As such, it is very common to treat authors as nodes connected by joint publications in so called knowledge-networks. Such and similar networks are frequently analyzed in the social sciences or in physics to identify universal structures, such as small world properties, or test hypotheses regarding processes of network formation, such as preferential attachment or homophily (Newman, 2001; Barabasi et al., 2002).

Besides their structural properties, networks are also of interest because they provide information about the position of individual nodes among a group of actors. Central positions might indicate importance or power in a network by controlling information flows between otherwise unrelated actors (Freeman, 1979). In the above mentioned knowledge-networks, some positions within the network might be better to access novel, external knowledge than others. Given that external knowledge is a highly valuable input for processes of invention and innovation, the question if and how network positions influence performance is widely studied especially in management and economics. Based on various types of networks, this field of research produced substantial empirical evidence showing that direct but also indirect connections matter for innovation performance (for reviews see Ozman, 2009; Cantner and Graf, 2011; Phelps et al., 2012; Hidalgo, 2015).

2.2 Networks as multimodal structures

While interaction and learning takes place among individuals, these networks can be analyzed at more aggregated levels to study interaction between groups of actors, such as organizations, industries, or geographical levels. A critical assumption is that knowledge and information are transmitted within nodes of a higher level of aggregation. At the organizational level, one is interested in collaborations between organizations (affiliations of the researchers) while knowledge flows within these organizations are assumed to be existent but usually not explicitly taken into account (Cantner and Graf, 2006; Adams et al., 2005; Guan et al., 2015a). Aggregation can also account for the geographical dimension as in studies on international collaboration, shedding light on knowledge flows between different regions (Wanzenböck et al., 2014, 2015) or countries (Owen-Smith et al., 2002; Wagner and Leydesdorff, 2005; Cantner and Rake, 2014).

Figure 1 displays the different levels or modes of networks that are used in the present study. Raw publication data is on the micro level and provides information about co-authorship between individuals. Information on the affiliations of the researchers is used to aggregate them to the meso level. These networks between organizations will be studied for each country separately to characterize the national research and innovation systems. By using information on the location of organizations, we reconstruct global networks – the macro level – of international collaboration. The position of countries within these networks provides valuable information about international embeddedness and (potential) access to global knowledge flows.

Our research aims at explaining differences between countries in terms of international embeddedness by looking at the structure of the national research systems as well as various other policies towards PV employed by national governments. As such, we contribute to the literature by linking meso and macro structures (Dopfer et al., 2004). The relationships and interactions between different levels of aggregation have recently been empirically tested. The underlying

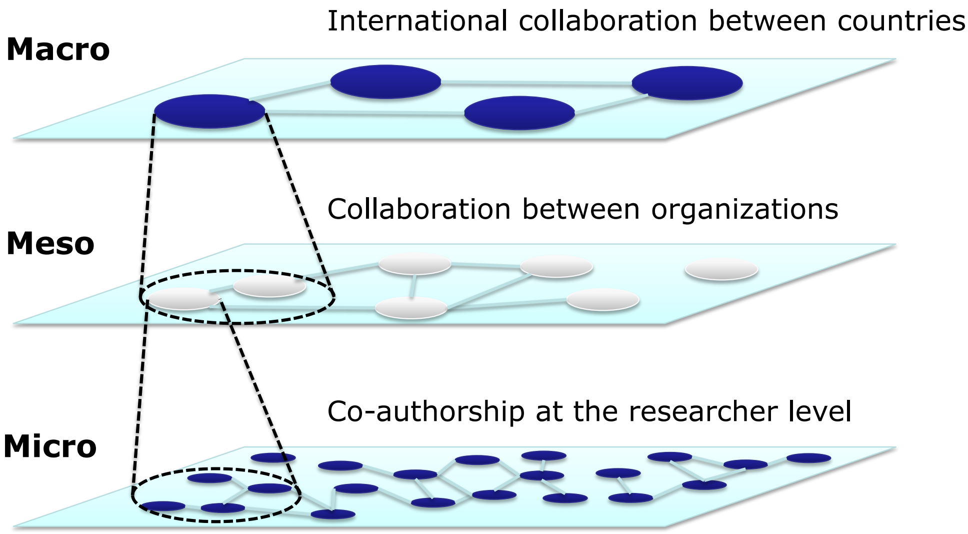


Figure 1: Multimodal structures

assumption of such analyses is that the network structures at different levels of aggregation influence each other (Gupta et al., 2007). For example, Guan et al. (2015b) analyze the influence of countries' positions in the global innovation network on the performance of actors in city level networks. In a similar vein, Paruchuri (2010) shows that inventor performance is influenced by the positions in intra- and interfirm networks.

2.3 Linking national research networks and global embeddedness

In the following, we derive hypotheses regarding the relation between the meso structures and macro embeddedness. Research networks on the national level can be thought of representing countries' research systems where different types of actors, such as universities, research institutes, companies, or governmental agencies interact in different ways. Collaboration on this level is determined by incentives, norms, or specific cultures towards collaboration which might differ between research fields and/or technologies but also between countries (Lundvall, 1992; Malerba, 2002; Wuchty et al., 2007). Despite the benefits of collaborating with partners that speak the same language or are proximate with respect to geographical or institutional dimensions (Boschma, 2005), the reasons for collaboration with national or international partners should be the same with a focus on the cognitive dimension. Therefore, if a country is characterized by a high level of collaboration on the national level, we expect the likelihood to cooperate on the international level to be higher as well.

Hypothesis 1 *Countries that are characterized by high collaboration intensity within the national research network, also collaborate more with international partners than countries with a low national collaboration intensity.*

Countries might rely on few strong actors (national champions) to follow a mission oriented national strategy to advance research in a specific field (Ergas, 1987). If countries have such strong leaders, it is often the strategic goal to advance knowledge mainly within the country with a reluctance to share knowledge internationally. Furthermore, Owen-Smith et al. (2002)

argue, that the decentralized organization of public research in the U.S. was relevant for their central position within the international life sciences knowledge network. Therefore, we expect centralized countries to be less open to international collaboration and less embedded in the international research network.

Hypothesis 2 *Countries with highly centralized national research networks are less embedded within the global knowledge network than countries with decentralized, diffusion oriented national networks.*

We also expect that functioning national research systems are characterized by internal as well as external openness due to a general, learned capability of collaboration and networking (Bathelt et al., 2004; Graf, 2011). Here, we assume that the functionality of a system in terms of knowledge exchange and learning is better the larger the share of actors who are connected to each other.

Hypothesis 3 *Countries with national research networks characterized by high connectivity are better embedded within the global knowledge network than countries with fragmented national networks.*

2.4 Policy influence on international embeddedness

PV is considered an environmentally friendly technology which generates electricity without emitting CO_2 or other harmful substances. However, it was only until recently that PV became cost competitive with conventional electricity generating technologies. Therefore, governments intervene to increase the efficiency of the technology, to decrease production costs, and to foster R&D in PV. In general, there are several approaches to support research activity and technological development which can be broadly categorized as demand pull or technology push policies (Mowery and Rosenberg, 1979; Jaffe et al., 2002; Groba and Breitschopf, 2013; Rogge and Reichardt, 2016). There is a growing theoretical and empirical literature in innovation and environmental economics which tries to understand how these policy interventions affect innovative output, especially in environmentally friendly technologies (see Jaffe et al., 2002; Kemp and Pontoglio, 2011; Groba and Breitschopf, 2013, for reviews). In the case of scientific research and collaboration, evaluations of such interventions are scarce and focuses on direct funding only.[1] In the following, we derive hypotheses regarding the influence of different policies towards renewable energies and PV in particular on the international embeddedness of countries in the global research network.

Technology push instruments are motivated by positive externalities or technological spillovers which lead to underinvestment in R&D. R&D subsidies are a classic example of such policies as they foster research activities by public and private actors (Arrow, 1962). Several studies in the economics of innovation show that R&D subsidies help to increase inventive activity (Watanabe et al., 2000; Johnstone et al., 2010; Peters et al., 2012; Wangler, 2013) and networking (Cantner et al., 2016) in PV research. Concerning general effects of technology push instruments on

[1] However, several studies focus on the micro (researcher) or meso (institute) level and find usually a positive effect of funding on publication output (see Ebadi and Schiffauerova, 2013, for a review).

publications, Crespi and Geuna (2008) find that on the macro level expenditures on higher education research and development increase research output, while Popp (2016) shows that direct funding increases research output in energy research, especially in solar energy, but in both cases with a considerable time lag. Concerning the effect of such policies on collaboration and network structures, there is only limited evidence for the collaboration intensity at the micro (researcher) level. Based on survey data, Bozeman and Corley (2004) and Lee and Bozeman (2005) find that the availability of grants leads to larger researcher teams and more collaboration. In a similar vein, Ubfal and Maffioli (2011) find that Argentinian researchers who received a grant are better integrated in the scientific community. Adams et al. (2005) find that federally funded R&D, increase the number of papers, team size per publication, as well as international cooperation for US universities.

Hypothesis 4 *International embeddedness increases with the amount of funding towards research and development.*

Demand pull policies increase demand by creating (niche) markets for new or infant technologies. Thereby, they attract companies to engage in production and benefit from economies of scale and learning-by-doing effects. If firms are profitable, they generate internal funds to conduct research and inventive activities which also contribute to the advancement of a technology. Investment subsidies, quota systems, or feed-in-tariffs are typical examples for such policies. In the case of PV, countries implemented different approaches to support commercialization of PV which in most cases also increased inventive activity (Johnstone et al., 2010; Peters et al., 2012; Wangler, 2013) and research collaboration (Cantner et al., 2016). Public procurement is another form of demand pull policy which has shown positive effects on R&D activities (Geroski, 1990; Edler and Georghiou, 2007; Guerzoni and Raiteri, 2015). In the case of public procurement, governments create demand for societal needs and acts as a lead user by asking for sophisticated products with clearly defined characteristics. In the case of PV, the government was the first customer for PV cells to power satellites and space applications (Oliver and Jackson, 1999; Petroni et al., 2010; West, 2014), which can be considered public procurement. Since PV cells for aerospace needed to be as efficient as possible, research was conducted to fulfill advanced requirements and provide efficiency improvements until today.

Hypothesis 5 *International embeddedness increases with the amount of effective demand pull policies.*

Besides these targeted instruments, the Kyoto Protocol can also be considered as a policy instrument which should encourage research and inventive effort in PV. Ratifying the Kyoto Protocol shows some commitment towards emission reduction and, especially for the Annex B countries, it has binding targets (UNFCC, 1997). Since one way to achieve these targets is PV, countries might increase their research effort after ratifying the Protocol. Some studies show indeed that the ratification of the Kyoto Protocol fosters inventive activity for PV (Johnstone et al., 2010) and renewable energies in general (Nesta et al., 2014). Furthermore, the Kyoto Protocol contains instruments which foster international collaboration and knowledge transfer (Dechezleprêtre et al., 2008). These instruments, namely the clean development mechanism and joint implementation, increase international collaboration and form networks of knowledge transfer by itself (Kang and Park, 2013) which can lead to scientific collaboration between countries as well.

Hypothesis 6 *International embeddedness is larger for countries after ratifying the Kyoto Protocol.*

3 Scientific collaboration networks

3.1 Data: photovoltaic publications

Publications are frequently used to measure output and collaboration at early stages of the research and innovation process. Several recent bibliometric studies have focused on renewable energies (Suominen, 2014; Guan et al., 2015a; Poirier et al., 2015; Popp, 2016) and PV (Dong et al., 2012; Huang et al., 2013; Du et al., 2014; Stek and van Geenhuizen, 2015). We collect data on photovoltaic publications from Thomson Reuters Web of Science Core Collection[2]. The sample consists in total of 106,836 publications from 1946–2015 by 146 countries covering various scientific fields. Figure 2a depicts the number of publications over time. An exponential growth in the number of scientific publications which indicates the increased pervasiveness of PV research during the last decades is evident.

In the following analysis, we restrict the sample to the years from 1980 until 2015 since there are only few publications before 1980. Furthermore, policy makers started to put more emphasis on PV research as a response to the oil crisis in the 1970s and research took off globally. In the sample from 1980 to 2015 105,809 publications are included. We use information on affiliations as provided by Web of Science to assign papers to organizations and countries. Most publications are from China, the USA, and Japan (see Table 1) but also European countries are among the top publishing countries[3].

Concerning international collaboration, i.e. publications of co-authors with affiliations located in different countries, there are on average 1.26 different countries involved in each publication. European countries, especially the United Kingdom, France, and Spain are frequently involved in international collaboration whereas Asian countries, especially Taiwan and China are less involved internationally. Concerning the development over time, depicted in Figure 2b, there is a steep increase around 1996, which is most likely related to our original data source. The information on author affiliations in the Web of Science is more reliable from 1996 onwards. Keeping this potential problem in mind but in line with Adams et al. (2005), we observe an increasing trend in international collaboration with some notable differences between countries. Asian countries, especially Taiwan and China, do not collaborate extensively internationally and stay roughly at the same level. European countries frequently engage in international collaborations and increase their international activity over time. This increase for the European

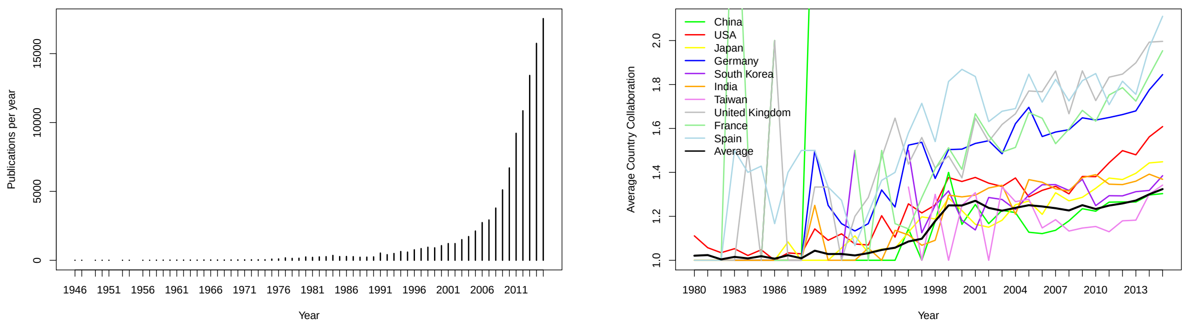
[2]The query is photovoltai* or solar cell* in the topic and title section on August 22^{nd} 2016. Only articles, proceedings papers, reviews or book chapters are considered.

[3]We do not calculate publication shares in case of international collaborations so the total number of publication per country does not match the total number of publications. Furthermore, we do not control for the quality of publications since our focus is on collaboration patterns and restricting the sample to some top journals would not represent the whole collaboration network. We also do not limit the scope of papers to specific research fields, since technological and social progress are interlinked.

Table 1: Number of publications and international collaboration by country from 1980 until 2015

Country	Publications	Share	International collaboration per publication
China	21,380	16.7%	1.266
USA	18,790	14.6%	1.451
Japan	9,196	7.2%	1.329
South Korea	8,985	7.0%	1.319
Germany	8,648	6.7%	1.662
India	5,728	4.5%	1.344
Taiwan	4,787	3.7%	1.214
United Kingdom	4,688	3.7%	1.837
France	3,851	3.0%	1.828
Spain	3,447	2.7%	1.739
Rest of World	38,843	30.3%	
Total	**128,343**	**100,0%**	**1.256**

countries could be related to the common labor market and the EU-Framework Programmes, which require pan-European collaboration.



(a) Annual PV publications. **(b)** Average country-collaboration per pub.

Figure 2: Overview of global PV publications.

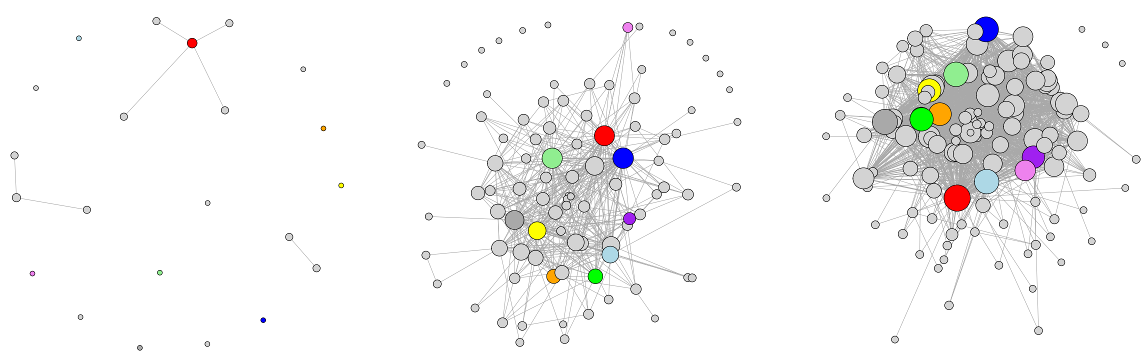
3.2 International research network

As pointed out above, we are interested in the structure and dynamics of scientific collaboration between countries. We employ methods of social network analysis (see Wassermann and Faust, 1994) to elaborate on the countries' collaboration pattern and embeddedness in the international research network. To analyze the networks over time, we use three-year moving windows. Thereby we account for persistence and decay of collaboration, since the date of publication is just a point in time, while the actual collaboration existed before and maybe persisted after the publication (Fleming et al., 2007; Schilling and Phelps, 2007). We reconstruct undirected international research networks using publications from 1980 until 2015, i.e. the first network covers the period 1980 to 1982 and the last network covers 2013 to 2015 leading to 34 overlapping observation periods. Three of these reconstructed international networks are illustrated in Figure 3.

We calculate several indicators to describe the development of the international collaboration network over time (see Figure 4). The number of nodes (i.e. countries), which indicates the size of the network, increases steadily (see Figure 4a). The mean degree measures the average number of connections of a node, i.e. the number of distinct co-authoring countries. Here, we see a steady increase, indicating that on average countries become increasingly embedded within the global network. The declining number of components also shows that the countries are getting increasingly interconnected and hardly any country performs research without international collaboration by the end of our observation period. This can also be seen in the share of isolates, countries which are not connected to another country, which diminishes drastically (see Figure 4b).

Concerning the importance of different countries in the network, we use the concept of network centralization. These measures are less concerned with the overall connectedness but rather with the specific structure of relations and relative positions of nodes. We use two centralization measures to account for the concentration of linkages on few nodes (degree centralization) and the dependence on nodes that connect many other nodes (betweenness centralization) proposed by Freeman (1979). Both measures are equal to 1 in a star network, in which all nodes are connected to one central node but not among each other, and take a value of 0 for networks without prominent positions, such as a ring or a complete graph. In Figure 4b, we present degree and betweenness centralization for the network. The degree centralization increases constantly over time, indicating that there are some countries that are way more interconnected than the average. The development of betweenness centralization shows that the concentration of knowledge flows increases during the early periods but diminishes throughout the last periods. Additionally, transitivity indicates the likelihood that adjacent nodes of a node are connected. For the global network, we see that except for the early phase transitivity increases constantly. Apparently, countries increasingly form densely connected clusters. Network density, which is the share of all present connections in all possible connections, increases despite network growth, indicating an over-proportional increase in linkage formation.

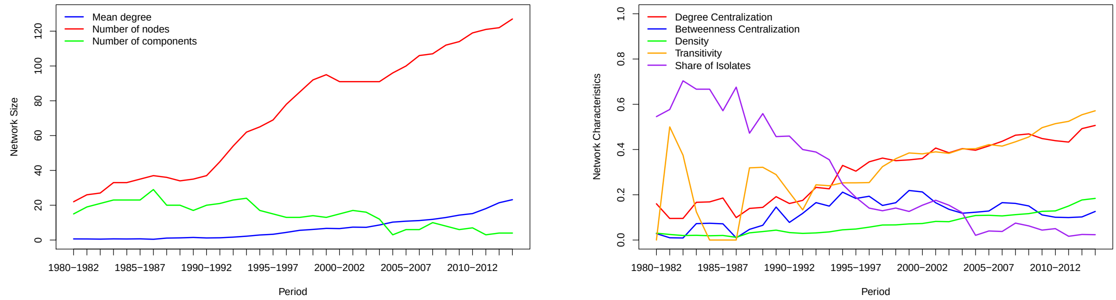
Regarding countries' positions within the global network, we focus on four measures of research performance and international embeddedness: Number of publications, degree, flow betweennes, and k-core per country. The number of publications per country indicates the



(a) Period 1980–1982. **(b)** Period 2003–2005. **(c)** Period 2013–2015.

(Colored nodes refer to the countries presented in Figure 6)

Figure 3: International research network for three periods.



(a) Network size. **(b)** Network Characteristics.

Figure 4: Evolution of the international research network.

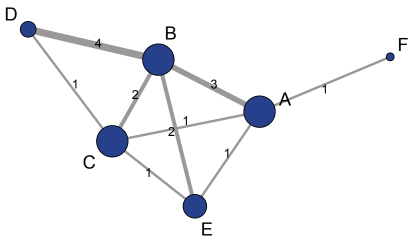


Figure 5: Example network.

Table 2: Example data.

Node	Degree	Flow Betweenness	K-Core
A	4	18	3
B	4	36	3
C	4	12	3
D	2	4	2
E	3	10	3
F	1	0	1

research output of a country. Degree, flow betweenness, and k-core are different concepts of centrality, all related to the number of connections. Degree is a simple count of the number of connections irrespective of their intensity, while flow betweenness considers the intensity but also the relative position within the whole network (Freeman et al., 1991). The k-core of a graph is the maximal subgraph in which every node has at least degree k (Seidman, 1983). Figure 5 and Table 2 show a simple example to point out the differences between the three concepts. Nodes A and B in the example have the same degree, both are connected to four other nodes. But if we consider flow betweenness, we see that node B is much more central than A. B is better connected to its neighboring nodes than A which puts B a better position in the network to access external knowledge. However, it has to be noted that degree is limited by the number of nodes in the network, while flow betweenness is more or less unrestricted. This measure not only accounts for the number of collaboration partners (A still has more access to knowledge than the other nodes) but also for the quality of cooperation partners. The k-core tells us if a node is member of the network core or rather of its periphery. Here, we see that nodes A, B, C, and E form the core in which every node has a degree of at least three, while D and F are in a more peripheral position.

Figure 6 depicts the development of these four measures for the top ten countries over time. The number of publications was highest in the USA until the last five periods, when China took over the lead. There is a strong increase in the number of publications from Asian countries. Besides China, also South Korea, India, and Taiwan are catching up. Japan was among the most publishing countries from early on, but is eventually outmatched by South Korea and Germany.

The degree shows an interesting development over time (the maximum for degree is limited by the size of the network, see Figure 4a). Surprisingly, Spain has the highest degree in some of the early periods but was again overtaken by the USA, which together with Germany has most

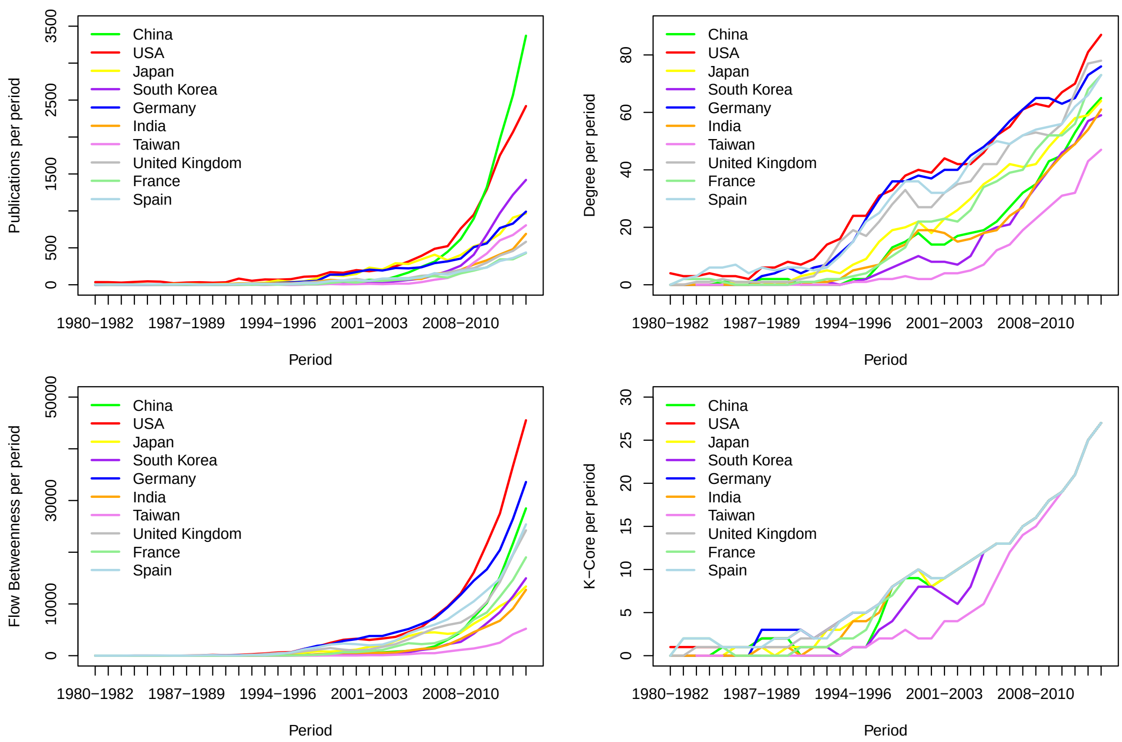


Figure 6: Network measures for top ten publishing countries.

connections over time. Both are connected to about 70% and 60% respectively of all countries in the last period. Furthermore, the USA and European countries have a higher degree than Asian countries for most of the time, and especially Taiwan is lagging behind. A similar pattern can be observed for flow betweenness, where the USA and Germany are on top. However, in the last periods China caught up and rages among the top three countries. This indicates that China, even though it has a lower degree than European countries, is connected to well embedded actors and has better access to knowledge. However, again, Taiwan is least embedded among the top ten countries, surpassed by India and Japan. The k-core shows no surprising development. Over time all countries join the core group within the network. There is very low variation over time and besides Taiwan, all countries quickly connect to the central core.

So far, we exemplified general trends of network development by looking at the top ten publishing countries. To analyze the underlying dynamics for all countries, we compare their relative position in the network over time. We rank all countries according to their degree in period 2003–2005 and compare this ranking with the periods 2008–2010 and 2013–2015. This gives us a Salter-Curve like representation of the dynamics in the network (see Figure 7). We see that at the top of the ranking the changes are marginal, while there is quite some turbulence in the middle. Among the top actors, especially Mexico is loosing its position, while most of the other countries stay rather stable. Qatar, the United Arab Emirates, Serbia and Malaysia are the countries which improve the most. Some other Arab countries improve their position as well. The top 15 as well as the 15 countries with the highest movement in the ranking are shown in Appendix A.1.

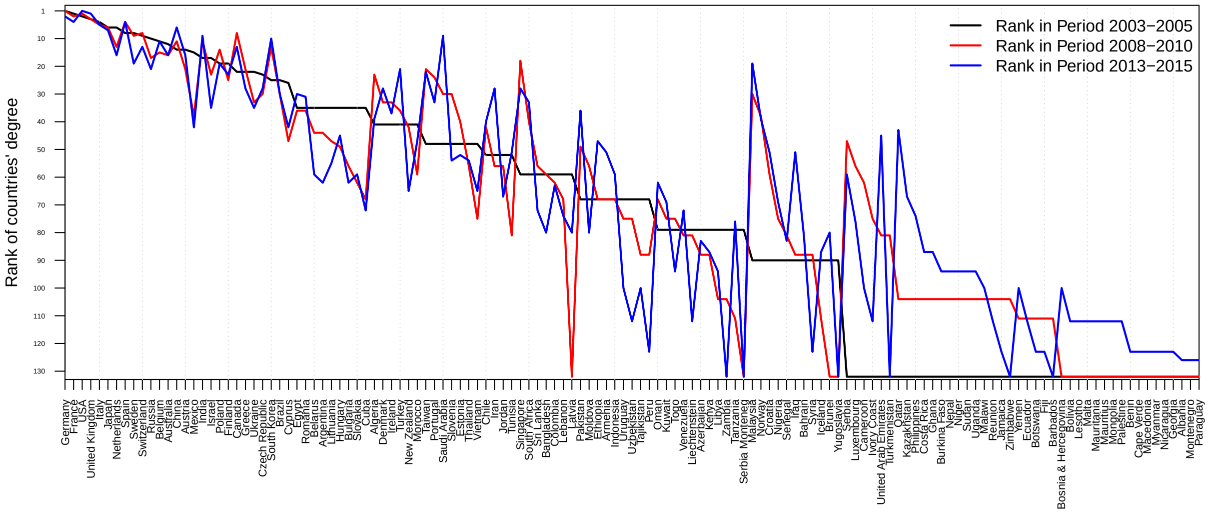


Figure 7: Rank of the degree of countries.

3.3 National research networks

In the following, the structure of interaction within each country is analyzed. Information on author affiliations allows us to reconstruct national research networks. Here, nodes represent different organizations, such as universities, research institutes, or companies and edges represent joint publications of researchers with different affiliations[4]. We reconstruct national research networks for all countries in our sample[5]. Again, we present network measures for the top ten publishing countries in Figure 8 to illustrate the general patterns of research activity and network development.

We observe an exponential increase in network size, indicating that more organizations emerge and engage in PV research. But there are notable differences between countries. While China and India experienced vast growth especially in the last periods, other countries, most notably the United Kingdom, show hardly any increase in the number of actors. Concerning the connections among these actors in the research system, mean strength (degree, weighted by the intensity of the connection) is increasing in all countries. Especially Taiwan and South Korea are very well connected at the national level. This is remarkable, since they are not that well connected internationally, as shown above (Table 1 and Figure 6). Another interesting case is India, which shows a very large increase in the number of nodes, but not with respect to mean strength, which indicates that there might be some deficits in domestic collaboration. In general, Asian countries seem to have a higher internal connectivity than European countries in the last periods.

Further indicators add to our understanding of the development of structural differences between national research networks. The share of actors in the main component takes the size of the largest component over the size of the network.[6] This measure increases in all countries

[4]Since we are interested in the structure of national research systems (and use its structural properties to explain global network positions, i.e. international collaboration in Section 4), we exclude cooperation partners in foreign countries

[5]Since the affiliation data is quite noisy, we consider only the organization name and neglect information about departments or other subsidiary information.

[6]The share of actors in the main component is sensitive for small networks and can lead to extreme values as

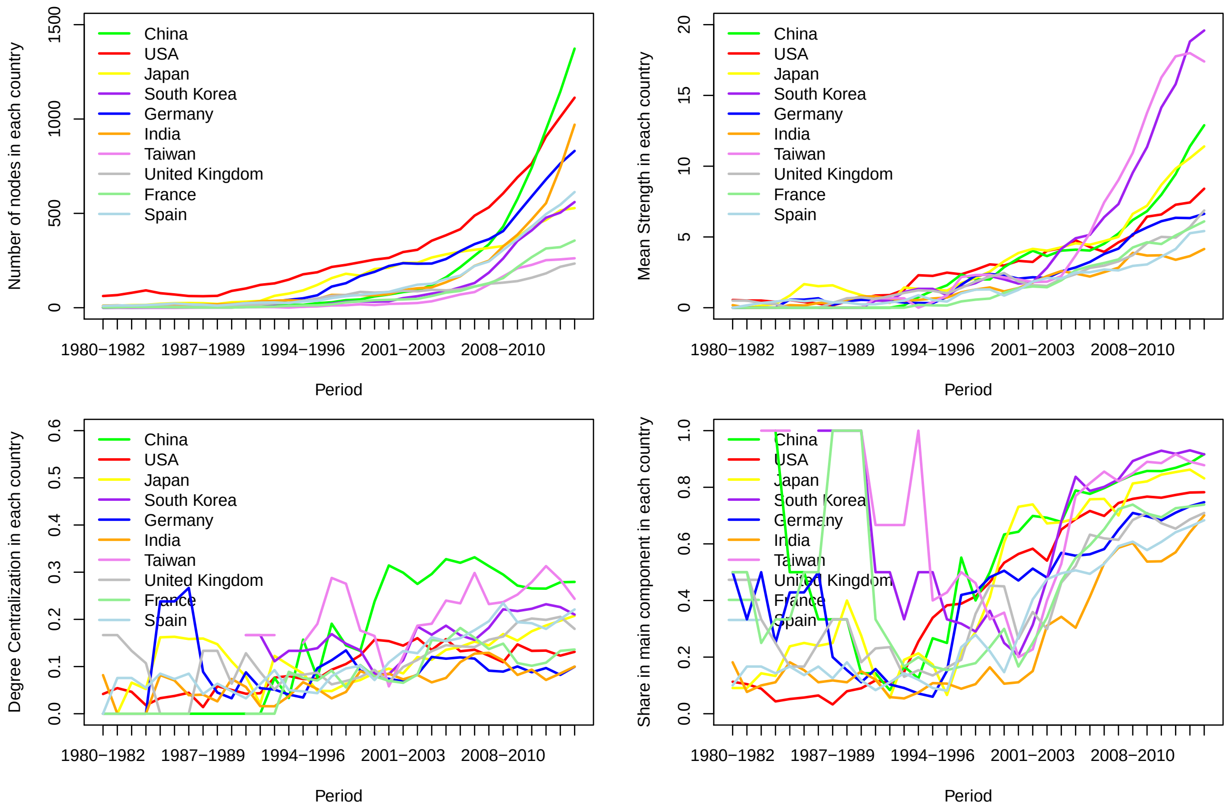


Figure 8: National network properties of for top ten publishing countries.

from the mid 1990s onwards indicating that the networks become less fragmented over time with the potential for knowledge flows between an increasing number of actors. Degree centralization accounts for the concentration of links in the network. It does not show a clear trend as the other structural measures and there is quite some variation between countries. Especially Taiwan, China, and South Korea appear to have a more centralized research systems in PV than e.g. Germany, India, the USA, or France.

4 Explaining embeddedness in the international research network

The embeddedness of a country in the international research network might be influenced by different objectives, economic circumstances, strategic decisions, or geographic location. We are interested in the effect of two particular influencing factors; i) the structural properties of the *national research network* and ii) *national policies towards PV*, e.g. by introducing and supporting research activities. In this section, we test the hypotheses derived in Sections 2.3 and 2.4. The variables are defined in Section 4.1, followed by the description of our estimation strategy in Section 4.2. The results are presented in Section 4.3 and their robustness is checked in Section 4.4.

seen in the first periods.

4.1 Variables

For the econometric analysis we use four sets of variables: dependent variables to describe international embeddedness of countries in the global PV research network and independent variables characterizing the national networks, national policies related to PV and renewable energies as well as controls. We conduct the analysis for the period 1980–2015, a robustness check for the sub-period 1997–2015 is discussed in Section 4.4. Since we use three-year moving windows for international and national network measures, a period serves as an observation and the starting year of the period refers to the year of observation. So the first period 1980–1982 is the observation for 1980 and the second period, 1981–1983 is the observation for 1981. Summary statistics of the variables are presented in Table 3. The correlations between the variables are documented in the Appendix A.3.

Dependent Variables – International embeddedness: The four dependent variables *publications*, *degree*, *flow-betweenness*, and *k-core* (as discussed in Section 3.2) measure countries' performance and international embeddedness. *Publications* accounts for the research output and can be seen as a benchmark how the national research system and policy influence performance. The three network variables emphasize different aspects of international embeddedness, i.e. how well a country is connected to other countries and how important a country is in terms of knowledge transfer between other countries.

National network variables: We use three properties of the national research networks as explanatory variables to account for the characteristics of the respective innovation systems (see Section 3.3). *Mean strength* measures the intensity of interaction, *degree centralization* indicates the concentration of linkages, i.e. the importance of 'national champions', and the *share in main component* to account for the overall potential of knowledge flows inside the country if the national network is well connected.

Policy variables: Several variables are used to operationalize national policies towards PV and renewable energies in particular or climate change in general. To account for technology push policies towards PV research, we use *PV R&D expenditures* by the government for PV in Mio US$ (IEA, 2016). However, this information is only available for some countries and not for all years. Whenever only a few years of observation for a country are missing, we interpolate R&D data and add a dummy to control for a possible effect of interpolation. Furthermore, we use the logarithm of annually *installed PV capacity* in MW (IEA, 2016), as a proxy for demand pull. Since PV is only recently price competitive, any installation must be somehow subsidized by the government. This measure is frequently used in the literature because it accounts for the effectiveness of a variety of policy instruments in inducing demand (Johnstone et al., 2010; Peters et al., 2012; Wangler, 2013; Cantner et al., 2016). Additionally, we use data on satellites to proxy public procurement in PV, since satellites were the first major application of PV and require until today the highest efficiency which is achieved by constant research activity (Oliver and Jackson, 1999; Petroni et al., 2010; West, 2014). We use the *cumulated number of satellites*

Table 3: Variable descriptive statistics 1980–1982 until 2013–2015.

	Min.	Median	Mean	Max.	SD	Obs.
Dependent variables						
Publications$_t$	0.000	0.000	17.057	3371.000	111.068	4964
Degree$_t$	0.000	3.000	9.203	87.000	13.724	2488
Flow Betweenness$_t$	0.000	52.000	760.922	45521.000	2663.286	2488
K-Core$_t$	0.000	3.000	5.599	27.000	6.587	2488
National network variables						
Mean Strength$_t$	0.000	0.500	1.171	19.589	1.940	2488
Degree Centralization$_t$	0.000	0.119	0.123	0.667	0.115	1937
Share in Main Component$_t$	0.033	0.500	0.585	1.000	0.300	2488
National policy variables						
Kyoto Ratification$_{t-1}$	0.000	0.000	0.276	1.000	0.447	4964
Cum. Number of Satellites$_{t-1}$	0.000	0.000	31.311	3412.000	263.446	4964
Installed PV Capacity$_{t-1}$	0.000	0.000	1.097	9.138	1.979	748
PV R&D Exp.$_{t-1}$	0.000	2.604	17.135	395.660	38.755	731
PV R&D Exp. interp. Dummy$_{t-1}$	0.000	0.000	0.079	1.000	0.270	986
Controls						
GDP per Capita$_{t-1}$	428.150	7392.135	13481.597	249579.559	17014.726	4440
EU Membership$_t$	0.000	0.000	0.114	1.000	0.318	4964
Conventional R&D Exp.$_{t-1}$	0.000	51.908	387.259	6110.350	818.237	695

deployed over time[7] to proxy the effort and commitment of a country towards the aerospace sector.[8] *Kyoto Ratification* is a dummy variable which takes a value of 1 in each year in which a country has ratified the Kyoto Protocol and 0 otherwise. It serves as an indicator for countries' commitment towards emission reduction.

Control Variables: We use the *GDP per Capita* provided by the Penn World Table (Feenstra et al., 2015) to account for countries' general state of development. Furthermore, national *conventional R&D expenditures* for fossil and nuclear energy research are employed to account for research activity in the energy sector (IEA, 2016). Since we expect that the common EU research area fosters collaboration between European research partners (Defazio et al., 2009), we control for *EU Membership* in all models, except for the short period full models in table A.4.

4.2 Estimation strategy

We conduct our analysis using unbalanced OLS-panel regression controlling for country and time fixed effects to account for the differences between countries but also for time effects such as general economic circumstances. Since we are interested in the causal effect of the policies, we lag the policy variables by one year. This allows to estimate the effect of these variables on the position within the network of the following three years[9]. We do not lag the national network

[7] The data was collected from http://satellitedebris.net/Database/LaunchHistoryView.php on May 2^{nd} 2015.

[8] We considered different ways to operationalize public procurement. Using the deployed satellites per year is another possibility but also using a dummy from the year onwards a country deployed its first satellite or cumulating the years from the first deployed satellite onwards as a knowledge stock. The results are available on request.

[9] As explained in Section 3.2, networks are reconstructed for overlapping 3-year periods.

variables, since we assume that actors decide in the same period about all of their cooperation partners. To account for heteroscedasticity, we report robust standard errors. Indexing countries by i and time by t, the generic regression model is the following:

$$\text{Embeddedness}_{it} = \beta_1 \text{Network Structure}_{it} + \beta_2 \text{Policy}_{it-1} + \beta_3 \text{Controls}_{it-1} + \text{FE}_i + \text{FE}_t + \varepsilon$$

We use two model specifications due to the lack of policy variables for many countries. In the restricted models, we omit *installed PV capacity*, *PV R&D expenditures*, and *conventional R&D expenditures* which we only have for a few, developed countries and allows us to analyze the factors responsible for international embeddedness of 114 countries. The full models include all variables but the available data covers only 18 countries[10].

4.3 Results

With four measures for performance and international embeddedness and two specifications, we end up with eight regression models to analyze the effects of national network structure and policy intervention (Table 4).[11]

Publications: In the first two models, we estimate the effect on the number of publications. The restricted model 1 reveals that *mean strength* is a strong predictor of the number of publications while *degree centralization* has the expected negative effect on publications. The *share in main component* has no significant effect. Concerning the policy variables, *Kyoto Ratification* has no effect while public procurement proxied by the *cumulated number of satellites* shows a positive effect. In the full model 2, the inclusion of additional variables does not change these results. Fostering PV by means of demand pull (*installed PV capacity*) as well as technology push policies (*PV R&D expenditures*) has positive effects on the number of publications. The control variables are insignificant, except for the EU dummy which is negative in model 1.

Degree: The factors influencing international embeddedness in terms of *degree* are presented in models 3 and 4. In the restricted model 3, all variables show an effect in the expected direction. In the full model 4, however, a slightly different picture emerges. Here, *degree centralization* and *share in main component* as well as the *Kyoto Ratification* and *installed PV capacity* remain significant. Since *mean strength* is highly correlated with *installed PV capacity* (see Table 8), it might well be that the effect of the former is at least partly caught by the latter. *PV R&D expenditures* show no effect, whereas *conventional R&D expenditures* seem to negatively affect *degree*.

Flow Betweenness: *Flow betweenness* is analyzed in models 5 and 6. In the first model, all three structural properties of the national research networks are significant and supportive of

[10] These countries are: Australia, Austria, Belgium, Canada, Denmark, France, Germany, Italy, Japan, the Netherlands, Norway, Portugal, South Korea, Spain, Sweden, Switzerland, Turkey, and the USA.

[11] There is a rather high correlation between *mean strength* and *installed PV capacity* as well as between *R&D expenditures* and *conventional R&D expenditures*. We tested these variables separately to see if there are changes in the respective coefficients and standard errors. The results reveal hardly any changes, indicating that multicollinearity is not an issue. The results are available on request.

our hypotheses. Regarding the policy measures, *Kyoto Ratification* has no significant effects on embeddedness, while procurement in terms of *cumulated number of satellites* shows a strong positive effect. Again, and contrary to our expectation, the coefficient for *EU membership* is negative. In the second model, none of the network properties are significant and only the *cumulated number of satellites* and *installed PV capacity* exert a positive influence on international embeddedness and foster access to global knowledge flows.

K-Core: In the case of *k-core*, model 7 reveals that national collaboration in terms of *mean strength* and *share in main component* are positive predictors of membership in a higher level core of the global knowledge network. Furthermore, the *Kyoto Ratification* has a weakly significant effect. Both control variables have a positive significant effect. It is noteworthy that this is the only specification where *EU Membership* shows a positive influence. The full model 8 shows divergent and almost no significant results. The reason lies in the properties of this measure of embeddedness. Since the central core of the network is composed of many, highly interrelated countries (35 countries by the end of our observation period), nearly all 18 countries included in this model enter the core at some point, so that there is very little variation in the dependent variable (see Figure 6). As such, this variable does not discriminate between the most central countries as much as *degree* and *flow betweenness*. This is also indicated by the small adj. R^2, which is about an order of magnitude smaller than in most of the other regressions.

Summary: Overall, research performance and international embeddedness in the global research network are strongly influenced by the structure of the national research network as well as by national policies. As hypothesized for *mean strength* in H 1 intense collaboration within the national research network increases international embeddedness. This holds true for all models that include a large set of countries, regardless how embeddedness is measured. However, for the models which cover only 18 developed countries but include additional explanatory variables, this relationship does not hold for embeddedness, but for *publications*. Centralization of the national research system is detrimental for research output and H 2 gains support in the *degree* models and the *flow betweenness* model with the large sample. This indicates that countries which centralize their PV research activity and focus on 'national champions' are less embedded in the international network. Concerning the functioning of the national research system, H 3 assumes that connectedness as measured by *share in main component* has a positive effect on embeddedness. This argument finds support in the *degree* models as well as in the *flow betweenness* and *k-core* models for the large sample of countries. In general, the national network structure seems to be a good predictor of international embeddedness and research performance, but these results are sensitive to sample size and the concepts used for its measurement.

With respect to the influence of governmental intervention, H 4 assumes that direct subsidies for PV R&D increase embeddedness. However, this is not the case and we can only observe a positive effect on the number of publications. Apparently, research funds are a valuable input for research activities without direct effects on international collaboration. In general, demand side policies have a positive effect as proposed in H 5. If demand side policies are proxied by *installed PV capacity*, this holds true except for the *k-core*. If demand is induced by governments themselves in the form of public procurement, proxied by the *cumulated number of satellites*, this also holds for all cases except for *k-core* and *degree* in the small sample. Hypothesis 6 assumes that the *Kyoto Ratification* induces activities to foster renewable energies which might show in an increased embeddedness in the global PV research network. However, this is only the case for the *degree* models and for *k-core* in the large sample while there is no influence on research output and knowledge access in terms of *flow betweenness*. Overall, governmental interventions have an effect on international embeddedness, however, the instruments differ in their effect. Creating a market by means of demand side policies seems more effective for international embeddedness than the provision of research funds or a general commitment to mitigate climate change.

4.4 Robustness tests

We conduct a robustness test for the econometric analysis to account for possible inconsistencies in the original data. As mentioned in section 3.1, the way Web of Science stores affiliation data changed around 1996. Furthermore, with the disbandment of the Soviet Union, several countries left the sample and new ones emerged. To account for such effects beyond the already present time fixed effects, we perform regressions with a subsample of the data covering the periods 1997–1999 to 2013–2015. The results as well as the correlations and descriptive statistics are presented in Tables 7, 9, and 10 in the Appendix.

The regression results for this shorter but more reliable period are quite stable and there are only marginal differences to the results presented above. The significance of *mean strength* and *degree centralization* does not really change, however, the *share in main component* is no longer significant for *flow betweenness* and *k-core* while the negative effect on *publications* turns significant. Concerning the policy variables, *Kyoto Ratification* is no longer significant in the regressions with the large sample for *degree* and *k-core*. The *cumulated number of satellites* is now significant for *degree* as well. The *installed PV capacity* loses its significance in the regression for the publication. Interesting results emerge for the *PV R&D expenditures* which have a weak negative effect on *degree*. Furthermore, *conventional R&D expenditures* show a significant negative effect on the number of PV *publications*.

5 Discussion

The present study analyzed the global research network in photovoltaics based on an original dataset of scientific publications in the field of PV. We asked two broader research questions: first, how did the global research network, in which countries are connected via international co-authorship, evolve over time? And second, what are the country level determinants of international embeddedness? To answer the second question, we focused on two types of country characteristics that seem influential. The first set of factors is comprised of national policies towards renewable energies and climate change in general and towards PV in particular. Our results add to the broad literature that analyzes effects of policy on environmentally friendly innovation (e.g. Popp, 2002; Newell, 2010; Kemp and Pontoglio, 2011; Acemoglu et al., 2012) and the more recently upcoming literature on the policy mix for innovation (Flanagan et al., 2011; Rogge and Reichardt, 2016; Cantner et al., 2016). With the second set of factors we enter an emerging research field by relating country level network characteristics – the meso level –

Table 4: OLS Panel regression results for country embeddedness periods 1980–1982 until 2013–2015.

	Publications		Degree		Flow Betwenness		K-Core	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
National network variables								
Mean Strength$_t$	60.791***	30.512**	1.903***	0.189	571.828***	232.811	0.687***	0.040
	(17.171)	(12.120)	(0.409)	(0.200)	(202.855)	(285.449)	(0.147)	(0.104)
Degree Centralization$_t$	-334.948***	-280.621***	-16.865***	-15.026***	-5693.235***	-3693.407	-0.986	-1.346
	(72.106)	(95.600)	(3.703)	(4.842)	(1521.648)	(3248.624)	(1.242)	(1.553)
Share in Main Component$_t$	-36.932	-98.164	11.070***	10.409***	1522.974*	-1546.532	1.562**	0.490
	(41.722)	(82.777)	(2.373)	(2.896)	(826.979)	(1658.821)	(0.677)	(0.780)
Policy variables								
Kyoto Ratification$_{t-1}$	-7.117	-37.674	2.479**	3.479*	-22.110	80.441	0.665*	-0.723*
	(31.033)	(48.464)	(1.183)	(1.921)	(528.756)	(716.144)	(0.396)	(0.427)
Cum. Number of Satellites$_{t-1}$	1.008***	1.201***	0.026***	0.008	15.270***	16.597***	0.002	-0.003***
	(0.206)	(0.121)	(0.004)	(0.007)	(2.629)	(3.488)	(0.002)	(0.001)
Installed PV Capacity$_{t-1}$		36.823***		1.414***		1049.462***		-0.144
		(14.064)		(0.518)		(307.835)		(0.094)
PV R&D Exp.$_{t-1}$		0.588*		0.012		11.485		0.003
		(0.320)		(0.013)		(7.112)		(0.003)
PV R&D Exp. interp. Dummy$_{t-1}$		-191.626		2.459		-1998.050		-0.101
		(143.296)		(2.415)		(3397.267)		(0.252)
Control variables								
GDP per Capita$_{t-1}$	-0.002	-0.003	0.000***	0.000	0.019	-0.061	0.000**	0.000
	(0.002)	(0.003)	(0.000)	(0.000)	(0.028)	(0.059)	(0.000)	(0.000)
EU Membership$_t$	-30.716**	-4.351	0.278	2.103	-585.492*	665.253	1.175**	0.276
	(14.584)	(21.422)	(1.317)	(1.406)	(306.476)	(434.231)	(0.545)	(0.623)
Conventional R&D Exp.$_{t-1}$		0.060		-0.003*		0.312		-0.001
		(0.037)		(0.002)		(0.794)		(0.000)
Country fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
Adj. R2	0.395	0.548	0.396	0.412	0.307	0.403	0.199	0.050
n	114	18	114	18	114	18	114	18
T	34	34	34	34	34	34	34	34
N	1876	447	1876	447	1876	447	1876	447
df	1722	385	1722	385	1722	385	1722	385

Robust standard errors in parentheses. Sig. at *** 0.01, ** 0.5, * 0.1 level.

to macro level embeddedness. While there are some studies concerned with the effects on network structure on performance (e.g. Verspagen and Duysters, 2004; Uzzi et al., 2007; Fritsch and Graf, 2011), only few studies relate different levels of networks in a research or innovation context (Paruchuri, 2010; Guan et al., 2015b). Our empirical results show that country level network structures are highly relevant for international embeddedness but also for research performance. We argue that the structure of national networks should be interpreted as characteristics of the national research system that are also subject to decisions taken by policy makers.

With respect to the **evolution of structural properties of the global PV research network**, we observe in Figures 2 and 4 that research output and the resulting network of international research collaboration are constantly growing. This highlights the global awareness regarding renewable energies and PV in particular as possibilities to mitigate climate change, but also with respect to existing market opportunity worth exploiting (Oliver and Jackson, 1999; Zheng and Kammen, 2014). Especially Asian countries are catching up and in recent years overtaking European countries in terms of research output but also in actual PV production (Zheng and Kammen, 2014). We also observe an increase in collaboration over time, which has been found to be a general trend in research and innovation activities (Wuchty et al., 2007). However, there are some notable differences between countries. While European countries collaborate quite frequently with international partners, Asian countries conduct most of their research domestically. This might be related to cultural differences, geographic proximity, or national strategies. There is not only a vast increase in research output, but also in terms of the number of actors, which indicates that more and more countries engage in PV research. The reasons should be found in improved market opportunities or industrial policies (Mazzucato, 2013). Emerging countries (with respect to PV research) are quickly embedded in the global research network, as documented by the decreasing number of components and share of isolates. At the same time, mean degree, density as well as transitivity increase, which shows that the global system functions well and becomes increasingly connected. Nevertheless, there seems to be a centralization process going on, such that some countries form a highly interconnected core.

Regarding the **dynamics within the global network**, we see a constant growth process of the network, however, there are many changes of relative positions of countries. Figure 7 ranks countries according to their degree centrality over time to visualize the dynamics within the network. While we observe stability among the top five countries, some other top ranked countries cannot keep up with the pace of the others. Especially Mexico, Russia, and the Netherlands dropped in the ranking, despite a doubling of their number of connections. Further interesting changes appear in the middle and lower part of the ranking. Some countries which did not do research at all in the period 2000–2002 get well connected in the last period. Especially Malaysia moved among the top countries, which was induced by an overall political commitment to engage in PV (Muhammad-Sukki et al., 2012). Also countries in the MENA region improved their position notably due to strategic decisions taken by their governments (Griffiths, 2013). The improvement of some Asian countries, especially China, Taiwan, South Korea, and India, is rather moderate, given that nowadays they publish most of the research in PV.

We use regression analysis to understand the factors influencing international collaboration and the **embeddedness of countries** in the research network. The results are – at least partly

– sensitive to the centrality concept used to measure embeddedness, but as an overall result we conclude that cohesion and connectedness of the national network positively influence international embeddedness. Centralization of the national network, i.e. a focus on 'national champions,' seems to be detrimental for performance and embeddedness. This implies that functioning national research systems in which actors are well connected, diverse, and decentralized are supportive of research output and international embeddedness. However, the establishment of an institutional systems conducive for such structures is certainly influenced by policy intervention and strategic decisions of governments.

Policy instruments have a differential effect on international embeddedness. R&D expenditures for PV, which are the most direct way to support research activity, are only beneficial for publication output, which is in line with previous findings (Adams et al., 2005; Popp, 2016). Contrary to previous findings by Adams et al. (2005), we find no significant influence on international embeddedness. Apparently, countries mainly strengthen their internal capabilities by fostering domestic research activities. However, since such domestic R&D grants have been found to increase collaboration within the country (Adams et al., 2005; Cantner et al., 2016), we cannot exclude that there is an indirect effect via the structure of the national research networks. Demand pull policies are a very robust predictor of research performance and international embeddedness across most estimated specifications. Even though they are not necessarily designed to induce R&D activities and innovation, they apparently provide incentives and create an environment that strengthens research and international collaboration. In addition to market oriented demand pull instruments, such as quotas or feed-in-tariffs, we also analyzed the effects of public procurement. Guerzoni and Raiteri (2015) have shown the relevance of public procurement for innovation. In our case, since we use the cumulative number of satellites to proxy procurement, this type of policy should be more relevant in the early years of the technology than during the last decades. However, procurement shows to be a very strong predictor of performance and international embeddedness not only in the long period 1980–2015 but also for the period 1997–2015. The performance effects hint at long term first-mover advantages and since spacecraft development is frequently conducted in multinational projects, it might well explain its effects on international embeddedness (Moloney et al., 2014). Countries that ratified the Kyoto Protocol have a more diverse set of international research partners even though it seems irrelevant for publication output. Hence, we do not find that such a general commitment to reduce emissions triggers research activities as it was found in the case of innovation (Johnstone et al., 2010; Nesta et al., 2014).

6 Conclusions

We present an attempt to explore the factors that affect the research performance as well as the embeddedness of countries in the international research network. Overall, we found that characteristics of national research networks as well as national policies are relevant factors for the explanation of countries' research performance and international embeddedness. We could also show that some policies are more effective in strengthening domestic research output, such as R&D expenditure, while others, such as a high connectedness of the national research network, seem more effective in fostering international embeddedness. Even though we did not explicitly test for its effect, we argue that embeddedness in the global research network is important for access to global knowledge flows.

As with any research, our study is not without limitations and some of them might affect the interpretation of our results more than others. Publication data is far from perfect to measure collaboration: the intensity of collaboration is not accounted for, collaboration might not be properly reflected in co-authorship, or affiliation information is incomplete (for further issues with publication data, see Katz and Martin, 1997; Laudel, 2002). Unfortunately, our analysis suffers from incomplete data, especially concerning R&D expenditures and demand pull instruments. These policy indicators are only available for a small – and certainly not random – subset of countries. Increasing the reliability and scope of the data would increase the reliability of our results and related studies. Finally, since we focus on a highly specific technology in which policy plays an important role (Cantner et al., 2016), we expect that especially our estimates on national policies are sensitive to the technology which limits generalizability.

In future research it would be important to understand how the different policies interact within the institutional framework to affect the network structures. The linkages between the national – meso – network and the global – macro – network remain another challenge for future inquiry. Furthermore, we would like to point out that not a single policy, but the combination of policies as well as the consistency and stringency of policies and governmental strategy influence each other and form a policy mix (Cantner et al., 2016; Rogge and Reichardt, 2016).

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A Appendix

A.1 Ranking of countries

Table 5: Rank of the Degree of the top 15 countries.

	Rank 2003-05	**Degree 2003-05**	**Degree 2008-10**	**Degree 2013-15**	**Δ Rank 03-05–08-10**	**Δ Rank 03-05–13-15**	**Rank 2013-15**
Germany	1	45	65	76	0	-2	3
France	2	43	54	73	-1	-3	5
USA	3	42	63	87	1	2	1
United Kingdom	4	36	53	78	0	2	2
Italy	5	34	44	68	-1	-1	6
Japan	7	30	42	64	0	-1	8
The Netherlands	7	30	34	54	-7	-10	17
Spain	9	26	47	73	4	4	5
Sweden	9	26	36	50	-1	-11	20
Switzerland	10	24	39	55	1	-4	14
Russia	11	22	25	49	-7	-11	22
Belgium	12	21	31	56	-4	0	12
Australia	13	19	27	54	-4	-4	17
China	15	18	35	65	3	8	7
Austria	15	18	23	54	-7	-2	17

Table 6: Rank of the Degree of the 15 most increasing countries.

	Rank 2003-05	**Degree 2003-05**	**Degree 2008-10**	**Degree 2013-15**	**Δ Rank 03-05–08-10**	**Δ Rank 03-05–13-15**	**Rank 2013-15**
Qatar	133	na	1	28	28	89	44
United Arab Emirates	133	na	3	27	51	87	46
Serbia	133	na	10	19	85	73	60
Malaysia	91	0	18	50	60	71	20
Kazakhstan	133	na	1	15	28	65	68
Philippines	133	na	1	11	28	58	75
Luxembourg	133	na	8	10	76	56	77
Norway	91	0	15	32	52	51	40
Costa Rica	133	na	1	5	28	45	88
Ghana	133	na	1	5	28	45	88
Croatia	91	0	7	25	31	39	52
Saudi Arabia	49	5	18	61	18	39	10
Iraq	91	0	2	25	2	39	52
Burkina Faso	133	na	1	4	28	38	95
Nepal	133	na	1	4	28	38	95

A.2 Descriptives small dataset

Table 7: Descriptive statistics of the 1997-1999 until 2013-2015 periods.

	Min.	Median	Mean	Max.	SD	Obs.
Dependent variables						
Publications_t	0.000	1.000	33.101	3371.000	155.350	2482
Degree_t	0.000	6.000	12.245	87.000	15.148	1760
Flow Betweenness_t	0.000	140.500	1064.318	45521.000	3115.896	1760
K-Core_t	0.000	5.000	7.444	27.000	6.993	1760
National network variables						
Mean Strength_t	0.000	0.953	1.538	19.589	2.180	1760
Degree Centralization_t	0.000	0.143	0.144	0.667	0.117	1465
Share in Main Component_t	0.073	0.520	0.583	1.000	0.277	1760
National policy variables						
Kyoto $\text{Ratification}_{t-1}$	0.000	1.000	0.551	1.000	0.497	2482
Cum. Number of Satellites_{t-1}	0.000	0.000	37.909	3412.000	302.727	2482
Installed PV Capacity_{t-1}	0.000	1.099	2.127	9.138	2.374	374
PV R&D Exp. t-1	0.000	3.435	17.249	395.660	37.759	408
PV R&D Exp. interp. Dummy_{t-1}	0.000	0.000	0.114	1.000	0.318	493
Controls						
GDP per Capita_{t-1}	428.150	8915.322	15706.152	164136.454	17703.133	2346
EU Membership_t	0.000	0.000	0.149	1.000	0.356	2482
Conventional R&D Exp._{t-1}	0.000	43.189	267.541	4552.800	636.316	393

A.3 Correlation tables

Table 8: Correlation table for the periods 1980-1982 until 2013-2015.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Publications_t	1.000														
2	Degree_t	0.601	1.000													
3	$\text{Flow Betweenness}_t$	0.831	0.778	1.000												
4	K-Core_t	0.440	0.896	0.588	1.000											
5	Mean Strength_t	0.617	0.750	0.592	0.724	1.000										
6	$\text{Degree Centralization}_t$	0.147	0.396	0.185	0.511	0.539	1.000									
7	$\text{Share in Main Component}_t$	0.080	-0.066	0.059	-0.134	0.084	0.391	1.000								
8	$\text{Kyoto Ratification}_{t-1}$	0.147	0.381	0.210	0.505	0.292	0.297	0.036	1.000							
9	$\text{Cum. Number of Satellites}_{t-1}$	0.191	0.191	0.177	0.105	0.095	0.104	-0.071	-0.010	1.000						
10	$\text{Installed PV Capacity}_{t-1}$	0.653	0.843	0.778	0.752	0.712	0.277	0.350	0.583	0.173	1.000					
11	$\text{PV R\&D Exp.}_{t-1}$	0.537	0.282	0.395	0.077	0.243	-0.111	-0.056	-0.060	0.652	0.315	1.000				
12	$\text{PV R\&D Exp. interp. Dummy}_{t-1}$	0.042	0.077	0.048	0.077	0.058	0.035	0.068	0.096	0.093	0.067	-0.058	1.000			
13	$\text{GDP per Capita}_{t-1}$	0.164	0.420	0.266	0.392	0.320	0.163	-0.116	0.132	0.081	0.396	0.178	0.144	1.000		
14	EU Membership_t	0.085	0.355	0.179	0.317	0.206	0.170	-0.137	0.175	-0.033	0.096	-0.172	0.047	0.310	1.000	
15	$\text{Conventional R\&D Exp.}_{t-1}$	0.247	0.011	0.106	-0.140	0.045	-0.232	-0.232	-0.148	0.446	0.141	0.761	-0.027	0.051	-0.250	1.000

Table 9: Correlation table for the periods 1997-1999 until 2013-2015.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Publications_t	1.000														
2	Degree_t	0.602	1.000													
3	$\text{Flow Betweenness}_t$	0.828	0.782	1.000												
4	K-Core_t	0.433	0.884	0.580	1.000											
5	Mean Strength_t	0.616	0.728	0.579	0.698	1.000										
6	$\text{Degree Centralization}_t$	0.120	0.337	0.145	0.455	0.499	1.000									
7	$\text{Share in Main Component}_t$	0.116	-0.039	0.083	-0.138	0.148	0.403	1.000								
8	$\text{Kyoto Ratification}_{t-1}$	0.074	0.245	0.136	0.354	0.162	0.171	0.064	1.000							
9	$\text{Cum. Number of Satellites}_{t-1}$	0.225	0.246	0.225	0.154	0.122	0.142	-0.024	-0.040	1.000						
10	$\text{Installed PV Capacity}_{t-1}$	0.613	0.814	0.743	0.678	0.609	0.029	0.498	0.384	0.194	1.000					
11	$\text{PV R\&D Exp.}_{t-1}$	0.741	0.509	0.585	0.216	0.408	-0.103	0.261	-0.109	0.677	0.471	1.000				
12	$\text{PV R\&D Exp. interp. Dummy}_{t-1}$	0.007	0.011	0.012	-0.010	0.000	-0.017	0.047	0.019	0.141	0.057	-0.036	1.000			
13	$\text{GDP per Capita}_{t-1}$	0.187	0.416	0.264	0.393	0.308	0.123	-0.073	0.078	0.073	0.226	0.204	0.125	1.000		
14	EU Membership_t	0.085	0.432	0.215	0.407	0.250	0.205	-0.057	0.172	-0.042	0.061	-0.258	0.084	0.358	1.000	
15	$\text{Conventional R\&D Exp.}_{t-1}$	0.496	0.334	0.330	0.098	0.297	-0.166	0.202	-0.087	0.406	0.409	0.746	0.031	0.134	-0.345	1.000

A.4 Regression results period 1997-1999 until 2013-2015

Table 10: OLS Panel regression results for country embeddedness periods 1997-1999 until 2013-2015.

	Publications		Degree		Flow Betwenness		K-Core	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
National network variables								
Mean Strength$_t$	60.772***	29.786***	1.947***	0.135	602.299***	312.425	0.658***	-0.009
	(15.923)	(9.814)	(0.297)	(0.208)	(189.412)	(274.486)	(0.136)	(0.137)
Degree Centralization$_t$	-292.796***	-273.114*	-11.071***	-12.213*	-4652.019***	-6442.561	-0.995	-0.392
	(85.106)	(157.808)	(2.832)	(6.566)	(1261.829)	(4937.240)	(1.371)	(1.655)
Share in Main Component$_t$	-84.859*	-72.020	6.204***	7.556**	747.921	-743.784	1.076	0.388
	(43.604)	(59.082)	(1.866)	(3.456)	(634.060)	(1522.624)	(0.765)	(1.153)
Policy variables								
Kyoto Ratification$_{t-1}$	-5.920	15.729	1.143	3.301**	-19.300	1187.732	0.309	-1.020*
	(20.202)	(25.504)	(0.860)	(1.591)	(338.253)	(801.680)	(0.402)	(0.521)
Cum. Number of Satellites$_{t-1}$	2.984***	2.994***	0.034***	0.011**	45.680***	43.204***	0.003	-0.003**
	(0.948)	(0.159)	(0.011)	(0.005)	(12.337)	(3.898)	(0.002)	(0.001)
Installed PV Capacity$_{t-1}$		10.312		0.622**		686.463***		-0.260**
		(8.020)		(0.276)		(248.741)		(0.115)
PV R&D Exp.$_{t-1}$		1.024***		-0.018*		20.052		0.000
		(0.326)		(0.010)		(14.594)		(0.002)
PV R&D Exp. interp. Dummy$_{t-1}$		-191.416		1.792		-2059.710		-0.221
		(138.991)		(2.134)		(3566.510)		(0.267)
Control variables								
GDP per Capita$_{t-1}$	-0.003*	-0.004*	0.000	0.000	0.000	-0.070	0.000*	0.000*
	(0.001)	(0.002)	(0.000)	(0.000)	(0.029)	(0.058)	(0.000)	(0.000)
EU Membership$_t$	-16.459*		-1.073		-682.242***		0.685	
	(9.861)		(1.580)		(257.069)		(0.721)	
Conventional R&D Exp.$_{t-1}$		-0.059**		0.002		-1.212		0.000
		(0.023)		(0.001)		(1.391)		(0.000)
Country fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
Adj. R2	0.436	0.582	0.307	0.202	0.335	0.410	0.143	0.174
n	114	18	114	18	114	18	114	18
T	17	17	17	17	17	17	17	17
N	1416	275	1416	275	1416	275	1416	275
df	1279	231	1279	231	1279	231	1279	231

Robust standard errors in parentheses. Sig. at *** 0.01, ** 0.5, * 0.1 level.

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