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International research networks: Determinants of country embeddedness

Holger Graf, Martin Kalthaus*

Friedrich Schiller University Jena, Department of Economics, Carl-Zeiß-Straße 3, 07743 Jena, Germany

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ABSTRACT

Research activities are increasingly global so that embeddedness in international knowledge networks is decisive for inventive and innovative performance. We analyze determinants of countries' embeddedness in the global photovoltaics knowledge network for the period 1980–2015 and argue that positions in this network are determined by the structure and functionality of national research systems and by instruments within the policy-mix for renewable energies. We show that cohesion and connectedness of the national research system positively affect international embeddedness, whereas centralized systems are detrimental to embeddedness. This indicates that a diffusion oriented research system allows better access to international knowledge flows. Policy instruments, especially demand side instruments, show a positive effect on embeddedness.

1. Introduction

The generation and diffusion of knowledge is a collective process and an increasingly global phenomenon. Collaboration among scientists and researchers steadily increased during the last decades and has led to more valuable output than individual research (Wuchty et al., 2007; Adams, 2013). While geographically proximate partners are typically preferred, it is especially collaboration with distant partners which allows access to diverse sets of knowledge with positive effects on performance (Bathelt et al., 2004; Cantner and Rake, 2014; Herstad et al., 2014). Collaboration with international partners leads to embeddedness in the global knowledge network. Here, embeddedness “refers to the process by which social relations shape economic action” (Uzzi, 1996, p. 674), and “research on embeddedness [...] advances our understanding of how social structure affects economic life” (Uzzi, 1997, p. 48). Being embedded in a network can therefore be understood as the position within a network in terms of connections to other actors (Wanzenböck et al., 2014, 2015). As such, embeddedness in the global knowledge network provides better access to knowledge, with positive effects on inventive and innovative performance, (Powell et al., 1999) and should therefore be considered as a policy objective.

With the rising importance of international research communities, countries strive to be integrated in global knowledge networks to access external knowledge and thereby secure technological and economic progress (Adams, 2012). While the importance of access to international knowledge flows has been emphasized for a long time (Bush, 1945), only in the past decades has policy put an emphasis on fostering access to and integration into global knowledge networks. Prominent examples include the establishment of an European Research Area, support of scientist mobility (via several programs, e.g. Marie Skłodowska-Curie, Fulbright, Erasmus+), and distinct national strategies or policies to engage in international collaboration.[1] Such programs as well as other factors substantially increased international collaboration and country embeddedness during the last decades, which seems to have enhanced the quality of national research (Wagner et al., 2015).

In this paper, we analyze the determinants of countries' embeddedness in the global photovoltaics (PV) knowledge network. We argue that the position of a country in this network is determined by two driving forces: First, by the structure and functionality of its innovation system (Nelson, 1993; Lundvall, 1992; Carlsson and Stankiewicz, 1991), and second, by active policy intervention to support R&D activities. With respect to the innovation system, we focus particularly on the interaction structure as a determinant of knowledge diffusion within the research system (OECD, 1997; 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 national networks, i.e. the functionality of the research system and its set-up, determines international collaboration and

* Corresponding author.
E-mail addresses: holger.graf@uni-jena.de (H. Graf), martin.kalthaus@uni-jena.de (M. Kalthaus).

[1] See Park and Leydesdorff (2010) and Kwon et al. (2012).

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embeddedness. With respect to policy intervention, we account for a variety of instruments that constitute the policy mix for renewable energies (Flanagan et al., 2011; Rogge and Reichardt, 2016). As such, we explore whether policy can create an environment conducive to international collaboration and increased embeddedness within the international research network.

Our empirical study is based on co-authorship information on scientific publications. This allows us to exploit the multimodal structure in publication data and link the national research network structure to country positions within the international research network. Scientific publications are an established tool for the measurement of knowledge generation or to track characteristics of the innovation process and collaboration intensity (Katz and Martin, 1997; Glänzel and Schubert, 2005). We focus on PV because it is a highly dynamic technology that has received strong governmental support and tackles a global problem by mitigating climate change. There is a large and growing literature on the effects of policies on innovation and diffusion in PV (e.g. Watanabe et al., 2000; Johnstone et al., 2010; Peters et al., 2012; Polzin et al., 2015; Cantner et al., 2016). However, we are not aware of studies on the influence of different policy measures on the embeddedness in international research networks in PV or in any other field.[2] We derive hypotheses about the effect of national network structures and policy interventions on countries' embeddedness and test them by OLS-panel regressions for all countries with scientific publications in the period from 1980 until 2015.

In line with Huang et al. (2013) or Du et al. (2014), we observe a steady increase in collaboration within the global PV research network. While a small group of countries remains central throughout all years, some countries catch up, whereas others lose relative positions in the network. With respect to the determinants of embeddedness, we find positive effects of overall cohesion and connectedness of the national research system. Among a subsample of OECD countries, the effect is not as pronounced because they all have well established and internationally embedded research systems (see also, Choi, 2012). Countries with a decentralized research network are internationally more embedded, indicating that diffusion oriented national research systems are more open towards external knowledge flows. With respect to the instruments of the policy mix, demand side instruments seem to be important for research and collaboration in PV, as has been shown elsewhere for inventive activity (Johnstone et al., 2010; Peters et al., 2012; Cantner et al., 2016). In particular, public procurement, proxied by the cumulative number of satellites, shows up as a robust predictor of embeddedness. This result fits well with the more general argument that governmental demand can increase research activity (Geroski, 1990; Edler and Georghiou, 2007; Aschhoff and Sofka, 2009; Guerzoni and Raiteri, 2015). With respect to direct R&D subsidies, we find ambiguous results; they only seem to encourage collaboration with already well embedded actors. The general commitment to mitigate climate change induces higher connectivity only for a subsample of OECD countries.

Our research contributes to the literature in several ways. We propose a novel approach to measure the functionality of a research system and show its influence on system performance, i.e. the relationship between meso structure and macro performance. We also provide insights on how the determinants depend on the operationalization of embeddedness. Furthermore, our results show that instruments of innovation policy not only increase research activities, but have effects on international collaboration and embeddedness. Lastly, we add public procurement to the already established instrument mix for renewable energies.

In the following section, we review the related literature and derive hypotheses. In Section 3, we describe the publication data and the international as well as the national collaboration networks. In Section 4, we present the econometric study where we estimate the effects of the national network structure and different policies on the embeddedness of countries. We discuss our results and conclude in Section 5.

2. Literature review and hypotheses

2.1. Networks of scientific collaboration

Knowledge generation is a cumulative and interactive process in which the relations between actors are key for knowledge exchange and diffusion (Dosi, 1988; Powell et al., 1996; Ahuja, 2000). The continuous increase in collaboration during the last decades has – amongst others – been attributed to an increasing specialization and division of labor because of the cumulative and dispersed nature of knowledge (Jones, 2009). There is vast empirical evidence that collaborative research leads to more valuable output than individual research (e.g. Adams et al., 2005; Wuchty et al., 2007; Adams, 2013). 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).

Not only has the tendency and intensity of collaboration and team size increased in science, but also the share of international collaborations and the geographical distance between co-authors (Wagner et al., 2015). By drawing on 21 million publications across all fields of science, Waltman et al. (2011) show that the average collaboration distance per publication has increased from 334 kilometers in 1980 to 1553 in 2009. For Europe, Hoekman et al. (2010) find a diminishing effect of geographical proximity on co-publishing, with territorial borders becoming less relevant. The reasons for these trends are manifold. The decline in travel cost, improvements in communication technologies, the rise of English as the common language in science, governmental programs, division of labor and specialization, joint research infrastructures, but also cultural traditions and norms have been put forward (Luukkonen et al., 1992; Wagner and Leydesdorff, 2005b; Waltman et al., 2011). The globalization of science is also driven by an increase in migrant scientists who typically have larger international research networks (Scellato et al., 2015). Wagner and Leydesdorff (2005b) systematize these factors into internal and external to the science system but postulate that international collaboration is an emergent feature of the science system due to preferential attachment. Even though there are differences in the levels of international collaboration, the trend towards increased internationalization can be observed in all disciplines (Wagner, 2005; Wagner et al., 2017).

The aggregate structure of collaboration is analyzed in what we refer to as knowledge networks. Co-authorship networks, where authors are treated as nodes connected by joint publications, are a prime example for such knowledge networks (Glänzel and Schubert, 2005). In one research stream, knowledge networks are analyzed to identify universal structures, such as small world properties, or to test hypotheses regarding processes of network formation, such as preferential attachment or homophily (Newman, 2001; Barabasi et al., 2002; Wagner and Leydesdorff, 2005b). 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). Some positions within the knowledge network might give an advantage for accessing novel, external knowledge. Given that external knowledge is a highly valuable input for processes of research and innovation, a second research stream is concerned with the questions regarding the influence of network positions on performance. Based on various types of knowledge networks, this field of research produced substantial empirical evidence showing that direct but also indirect connections matter for research and innovation performance. For

[2] Several bibliometric studies focus on PV publications from different perspectives (Dong et al., 2012; Huang et al., 2013; Du et al., 2014; Cho et al., 2015; Popp, 2016, 2017) but not with respect to the determinants of international collaboration or embeddedness.

reviews see Ozman (2009), Cantner and Graf (2011), Phelps et al. (2012), or Hidalgo (2016).

2.2. Networks as multimodal structures

While interaction and learning takes place among individuals, networks are analyzed at more aggregated levels to study interaction between groups of actors, such as organizations, industries, regions, or countries (Glänzel and Schubert, 2005). A critical assumption for such an aggregation is that knowledge and information are transmitted within those larger entities. 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 (Adams et al., 2005; Cantner and Graf, 2006; 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, 2005a; Cantner and Rake, 2014).

Fig. 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 about the affiliation of researchers is used for aggregation on the meso level. These networks between organizations on the country level provide insights on the structure of national research and innovation systems. By using information on the home country of organizations, global networks represent the macro level of international collaboration. The position of countries within these networks provides valuable information about international embeddedness in terms of participation in scientific communities and the potential to access global knowledge flows.

The relationships and interactions between different levels of aggregation have recently been empirically tested. The underlying 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 as representing countries' research systems where different types of actors, such as universities, research institutes, companies, or governmental agencies interact in various ways. Collaboration on this level is determined by incentives, norms, or specific cultures towards collaboration, which might differ

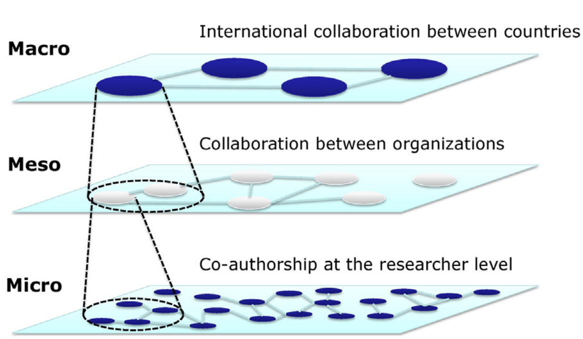


Fig. 1. Multimodal structures.

between research fields and/or technologies but also between countries (Lundvall, 1992; Malerba, 2002; Wuchty et al., 2007). While the cultural and technological determinants are typically beyond the reach of policy measures, there are several ways in which policy can shape the interaction structure by means of incentives, norms, and regulations (Smits and Kuhlmann, 2004). As such, the structure of the national research network is the result of a long-term process driven by path dependencies and guided by political influence.

In theory, the choice to collaborate should only be based on scholarly ground, however, this is typically not the only rationale. Scholars are biased towards collaboration with partners who speak the same language or are proximate with respect to geographical or institutional dimensions (Boschma, 2005; Hoekman et al., 2008). There is also ample evidence that collaboration choices are shaped by processes of preferential attachment, where successful and well connected stars attract even more collaboration partners (Barabasi et al., 2002; Wagner and Leydesdorff, 2005b; Lemarchand, 2012). In addition, choices are influenced by norms, habits, and routines. In an institutional environment where collaboration is the norm and past experience tells that collaboration is beneficial, the probability to collaborate can be expected to be higher than in one that rewards and/or exemplifies individualism. In sum, 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. The main reason is the complementarity between internal 'buzz' and global 'pipelines' where external linkages are especially fruitful if there is a high degree of local interaction (Bathelt et al., 2004; Morrison et al., 2013; Breschi and Lenzi, 2015).

Hypothesis 1: The intensity of national collaboration positively affects countries' international embeddedness.

The mission vs. diffusion dichotomy in science and innovation policy can help us understand the relationship between international embeddedness and centralization (or concentration) of the national research system. According to Ergas (1987), countries can promote a technology either for reasons of national sovereignty and international competitiveness (mission) or to deal with market failures (diffusion). Countries that pursue mission oriented strategies are typically characterized by few strong actors (national champions) (Ergas, 1987). If the strategic goal is to advance knowledge mainly within the country, there is a quite natural reluctance to share knowledge internationally. If, on the other hand, the policy goal is to solve a global problem, the international diffusion of knowledge should be most welcome. In that context, 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 countries with a centralized research system to be less open to international collaboration and less embedded in the international research network.

Hypothesis 2: Centralization of the national research network negatively affects countries' international embeddedness.

Functioning research systems are characterized by the ability to generate knowledge spillovers (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007). A prerequisite for knowledge diffusion and spillovers is the connectivity of the network as captured, for example, by the share of actors in the largest component (Fleming and Frenken, 2007). We expect that, in such integrative systems, internal as well as external openness go hand in hand. First, because national scientific communities need to be attractive for foreign researchers and capable of organizing international projects, conferences, etc. to strengthen international embeddedness and, second, due to a general, learned capability of collaboration and networking (Bathelt et al., 2004; Graf, 2011; OECD, 2014). Therefore, we propose that highly connected national research systems are more prone to international collaboration than fragmented ones.

Hypothesis 3: Connectivity within the national research system positively affects countries' international embeddedness.

2.4. Policy influence on international embeddedness

PV is considered an environmentally friendly technology that generates electricity without emitting CO_2 or other harmful substances. However, it was only recently that PV became cost competitive with conventional electricity generating technologies. Therefore, governments have intervened to foster R&D in PV to increase efficiency and to decrease production costs. In general, there are several approaches to support research activity and technological development within the broader policy mix (Flanagan et al., 2011; Rogge and Reichardt, 2016). The main instruments relate to demand pull or technology push policies (Mowery and Rosenberg, 1979). There is a growing theoretical and empirical literature in innovation and environmental economics that 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 focus on direct funding only.[3] 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 that 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; OECD, 1997). Several studies show that R&D subsidies 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 effects of technology push instruments on publications in general, 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 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 increases the number of papers, team size per publication, as well as international cooperation for US universities.

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

Demand pull policies increase demand by creating (niche) markets for new or infant technologies (Kemp et al., 1998; Nill and Kemp, 2009). 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 that, 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 that 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 of countries increases with the amount of effective demand pull policies.

Besides these targeted instruments, the Kyoto Protocol can also be considered as a policy instrument that should encourage research and development in PV. Ratifying the Kyoto Protocol shows 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 and engage in international collaboration 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 that 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 of countries is larger after ratifying the Kyoto Protocol.

We test these hypotheses in Section 4. In the following section, we explain the data and method to reconstruct collaboration networks on the international and national level and provide a short description of their developments.

Table 1
Number of publications and international collaboration by country 1980–2015.

Country	Publications	Share	International collaboration per publication
China	21,380	16.7%	1.266
USA	18,790	14.6%	1.451
Japan	9196	7.2%	1.329
South Korea	8985	7.0%	1.319
Germany	8648	6.7%	1.662
India	5728	4.5%	1.344
Taiwan	4787	3.7%	1.214
United Kingdom	4688	3.7%	1.837
France	3851	3.0%	1.828
Spain	3447	2.7%	1.739
Rest of World	38,843	30.3%	–
Total	128,343	100.0%	1.256

3. International and national collaboration networks

3.1. Data on photovoltaic publications

Publications are frequently used to measure output and collaboration at early stages of the research and innovation process. We collect data on PV publications from Thomson Reuters Web of Science Core Collection.[4] The sample consists in total of 106,836 publications from the years 1946–2015 written by authors from 146 countries covering

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

[4] The query used is photovoltai* or solar cell* in the title, abstract and keywords section on August 22nd 2016. Since we focus our research on PV only, we decided to be conservative and refrain from using more general search terms, such as "solar*" to minimize false positives at the cost of higher coverage. Only articles, proceedings papers, reviews or book chapters are considered. More than 98% of the publications are in English.

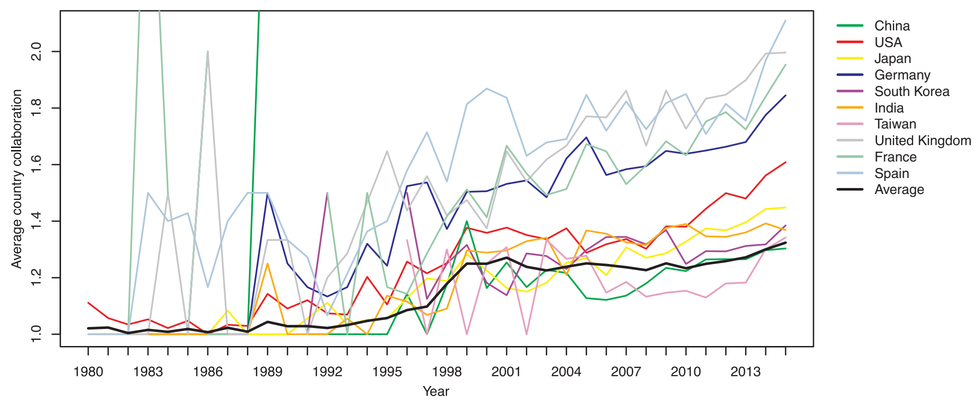


Fig. 2. Number of countries per publication.

various scientific fields. The number of publications grows exponentially over time, which indicates the increased pervasiveness of PV research during the last decades.

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.[5]

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 more frequently involved in international collaboration than Asian countries, especially Taiwan and China, which are less collaborative internationally. Concerning the development over time, depicted in Fig. 2, 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 countries could be related to the common labor market and the EU-Framework program, which require pan-European collaboration.

3.2. Structure and dynamics of the international research network

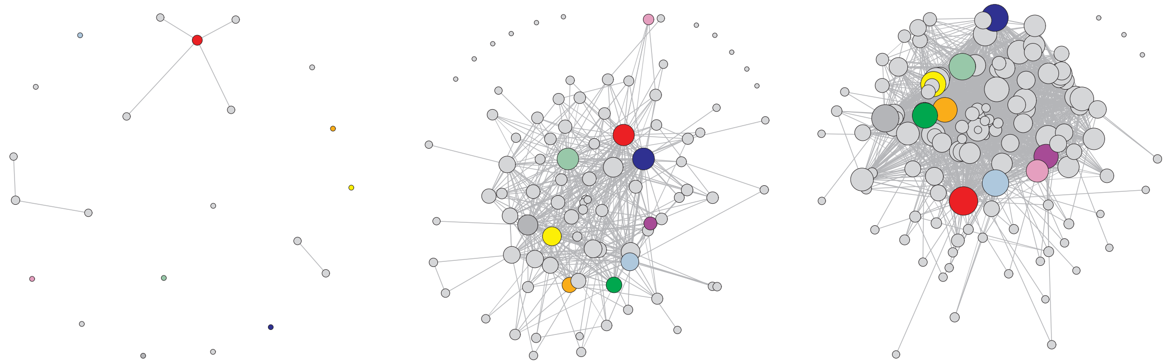
Before analyzing the determinants of embeddedness, we have to understand the structure and dynamics of scientific collaboration between countries. We employ methods of social network analysis (see Wassermann and Faust, 1994) to elaborate on the countries' collaboration pattern and embeddedness in the 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 may have persisted after the publication (Fleming et al., 2007; Schilling and Phelps, 2007).[6] 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. Fig. 3 displays three of these reconstructed international networks and illustrates how the network changes in terms of size and connectedness.

We calculate several indicators to describe the development of the international collaboration network over time (see Fig. 4). The number of nodes (i.e. countries), which indicates the size of the network, increases steadily (see Fig. 4a). The mean degree measures the average number of connections per 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 not connected to another country, which diminishes drastically (see Fig. 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 Fig. 4b, we present degree and betweenness centralization for the network. 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

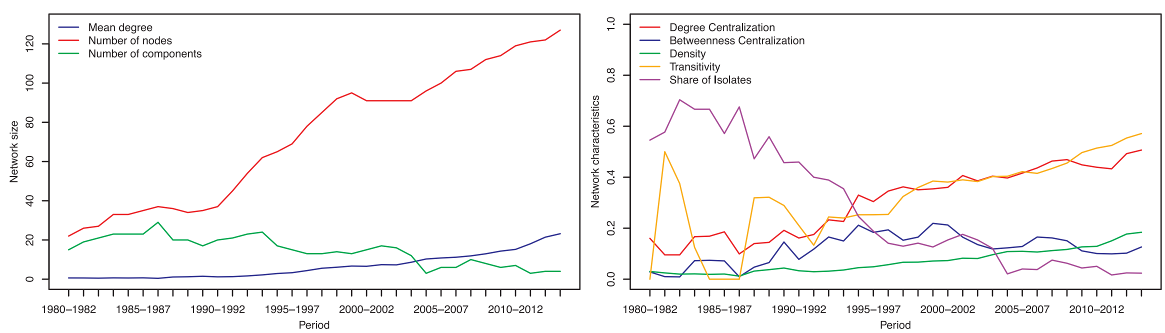
[5] Since the main focus of this paper is on collaboration, we do not calculate publication shares in case of international collaborations. Therefore, the total number of publications per country does not match the total number of publications. Furthermore, we do not control for the quality of publications 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.

[6] There is no consensus among network researchers regarding the correct length of the window. Some assume only the publication year (Wagner and Leydesdorff, 2005b), others three (Li et al., 2014), five (Li et al., 2013), or seven years (Fleming and Marx, 2006), and some do not account for a link decay at all (Breschi and Catalini, 2010). While this decision certainly influences the level of network metrics, it does not affect the direction of change. Therefore, it is up to the researcher to balance the trade-off between networks of higher density and connectedness, on the one side, and more observations over time on the other.



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

Fig. 3. International research network for three periods. **Note:** Node size is a function of the node's degree. Colored nodes refer to the countries presented in Fig. 2.



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

Fig. 4. Evolution of the international research network.

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 three measures of embeddedness. Degree, flow betweenness, and k-core are different concepts of centrality and embeddedness, 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 and 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). Higher values indicate membership in an increasingly cohesive subgroup that forms the network core.

Fig. 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

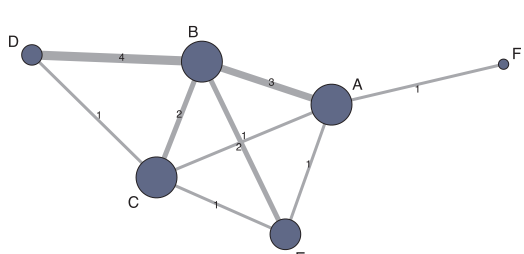


Fig. 5. Example network.

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

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 in 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.

Fig. 6 depicts the development of publications and the three measures of embeddedness for the top ten countries over time. The number of publications is highest for the USA until 2010, when China takes over the lead. In general, there is a strong increase in the number of publications from Asian countries. Besides China, also South Korea, India, and Taiwan catch up. Japan had been among the most publishing countries since early on, but was eventually outmatched by China, South Korea, and most recently by India. The same holds true for Germany.

With respect to measures of embeddedness, degree shows an

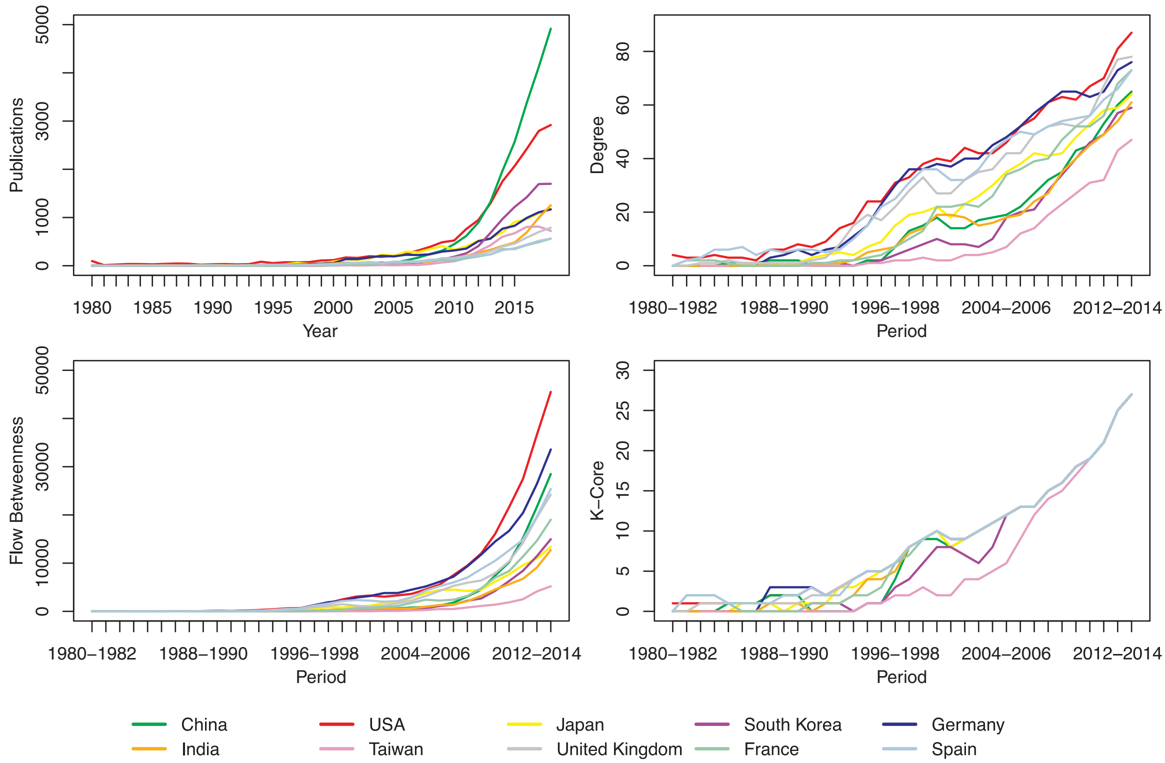


Fig. 6. Publications and network measures for top ten publishing countries.

interesting development (the maximum for degree is limited by the size of the network; see Fig. 4a). Surprisingly, Spain has the highest degree in some of the early periods but was overtaken by the USA, which together with Germany has the most 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, while especially Taiwan is lagging behind. A similar pattern can be observed for flow betweenness, where the USA and Germany have the highest values. However, in the last periods, China has caught up and ranges among the top three countries. This indicates that China, even though it has a lower degree than the presented European countries, is well embedded in terms of access to knowledge flows. 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 high publishing countries join the core group within the network. There is very little 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 Fig. 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 losing its position, while most of the other countries hold their positions. Qatar, the United Arab Emirates, Serbia, and Malaysia are the countries that have improved the most. Some other Arab countries improve their position as well. The top 15 as well as the 15 countries with the largest movement in the ranking are shown in Table 6 and 7 in the Appendix.

3.3. Development of the national research networks

In the following, we focus on the structure of interaction within each country. 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.[7] We reconstruct national research networks for all countries in our sample. Again, we present network measures for the top ten publishing countries in Fig. 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. However, notable differences between countries exist. While China and India experienced vast growth, especially in the latest 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 actors in Taiwan and South Korea are very well connected. This is remarkable, since they are not that well connected internationally, as shown above (Table 1 and Fig. 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 degree of internal interaction than European countries in the last periods.

Further indicators add to our understanding of the development of structural differences between national research networks. Degree

[7] 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. Furthermore, since the affiliation data are quite noisy, we consider only the organization name and neglect information about departments or other subsidiary information.

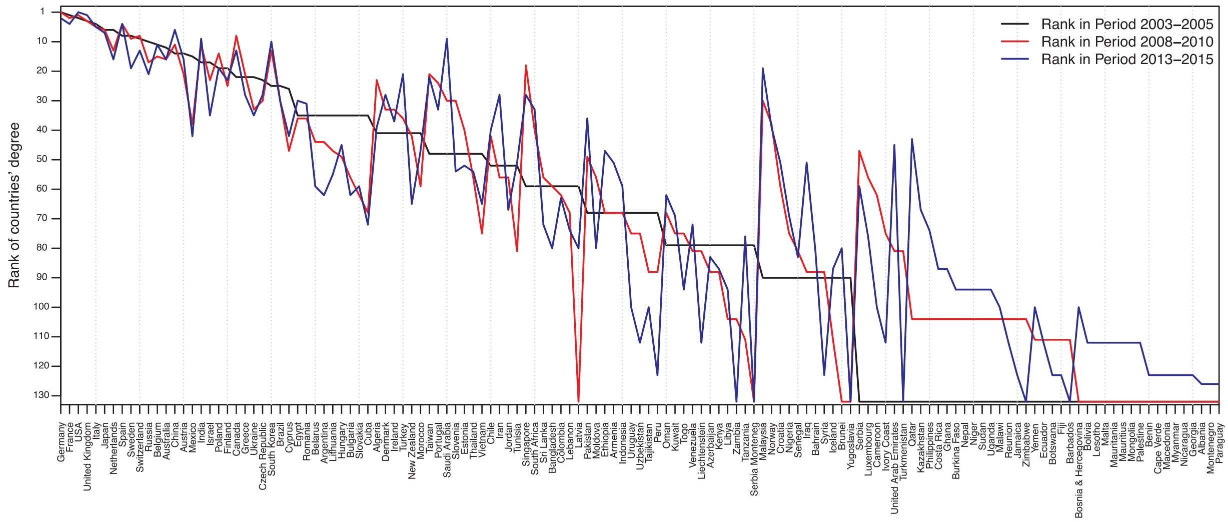


Fig. 7. Rank of the degree of countries.

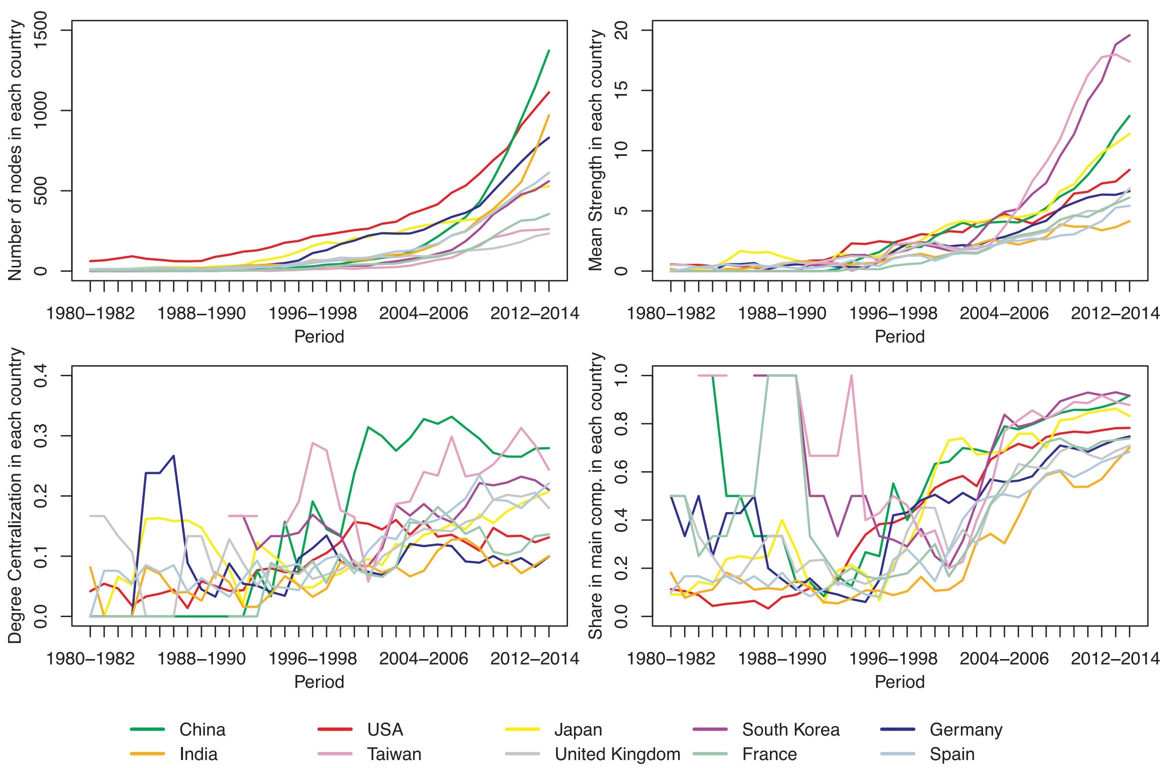


Fig. 8. Properties of the national research networks for top ten publishing countries.

centralization accounts for the concentration of links in the network. There is no clear trend, but we observe quite some variation between countries. Especially Taiwan, China, and South Korea appear to have more centralized research systems in PV than, e.g., Germany, India, the USA, or France. The share of actors in the main component is another indicator for the structure of the network and accounts for its connectivity. It takes the size of the largest component over the size of the network.[8] This measure increases in all 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 national actors.

[8] The share of actors in the main component is sensitive for small networks and can lead to extreme values as seen in the first periods.

4. Explaining embeddedness in the international research network

4.1. Variables

To test our hypotheses on the influence on embeddedness, 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 climate change, 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

Table 3
Variable descriptive statistics of the periods 1980–1982 until 2013–2015.

	Min.	Median	Mean	Max.	SD	Obs.
Dependent variables						
Degree_t	0.000	7.500	13.887	87.000	15.591	1540
$\text{Flow Betweenness}_t$	0.000	189.000	1210.045	45521.000	3305.788	1540
K-Core_t	0.000	6.000	8.115	27.000	7.097	1540
Publication_t	1.000	9.000	59.379	3371.000	202.121	1413
National network variables						
$\text{Mean Strength}_{t-3}$	0.000	0.800	1.258	16.264	1.613	1540
$\text{Degree Centralization}_{t-3}$	0.000	0.109	0.117	0.667	0.110	1540
$\text{Share in Main Component}_{t-3}$	0.033	0.429	0.436	1.000	0.221	1540
National policy variables						
$\text{Kyoto Ratification}_{t-1}$	0.000	1.000	0.508	1.000	0.500	1540
$\text{Cum. Number of Satellites}_{t-1}$	0.000	1.000	84.232	3412.000	429.341	1540
$\text{Installed PV Capacity}_{t-1}$	0.000	0.336	1.562	9.138	2.241	437
$\text{PV R\&D Exp.}_{t-1}$	0.000	8.754	27.928	395.660	47.136	437
$\text{PV R\&D Exp. interp. Dummy}_{t-1}$	0.000	0.000	0.071	1.000	0.257	437
Controls						
$\text{GDP per Capita}_{t-1}$	428.150	17,173.502	20,053.469	164,136.454	16,325.668	1540
$\text{EU Membership}_{t-1}$	0.000	0.000	0.281	1.000	0.450	1540

period refers to the year of observation. For example, 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 variables are documented in Table 9 in the Appendix.

4.1.1. Dependent variables – international embeddedness

The three dependent variables *degree*, *flow-betweenness*, and *k-core* (as discussed in Section 3.2) measure countries' international embeddedness and access to knowledge flows. 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.

4.1.2. 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* accounts for the overall potential of knowledge flows inside the country.

4.1.3. Policy variables

Several variables are used to operationalize national policies towards PV in particular and climate change mitigation in general. To account for technology push policies towards PV research, we use *PV R&D expenditures* by the government in Mio US$ (IEA, 2016). However, this information is only available for some OECD 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 (*PV R&D Exp. interp. Dummy*). Furthermore, we use the logarithm of annually *installed PV capacity* in megawatt (MW) (IEA, 2016), as a proxy for demand pull policies. Since PV has become only recently price competitive, any installation must have been somehow subsidized by the government. This measure is frequently used in the literature because it accounts for the effectiveness of a variety of demand inducing policy instruments (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 cell efficiencies, research activity is intensively conducted to increase performance (Oliver and Jackson, 1999; Petroni et al., 2010; West, 2014). We use the *cumulated number of satellites* deployed over time[9] to proxy the effort and commitment of a country towards the aerospace sector. *Kyoto Ratification* is a dummy variable that 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.

4.1.4. 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, countries that join the European research area can establish collaboration with other European members more easily and can benefit from European support schemes (Defazio et al., 2009). Therefore, we control for *EU Membership*.

4.2. Estimation strategy

We conduct our analysis using unbalanced OLS-panel regressions 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 national network variables by three years and policy variables by one year. This allows us to estimate the effect of these variables on the position within the network of the following three years.[10] To account for heteroscedasticity, we report robust standard errors. Indexing countries by i and time by t, the generic regression model is the following:

$$\text{Embeddedness}_{\text{it}} = \boldsymbol{\beta_1}\text{NetworkStructure}_{\text{it}-3} + \boldsymbol{\beta_2}\text{Policy}_{\text{it}-1} + \boldsymbol{\beta_3}\text{Controls}_{\text{it}-1} + \text{FE}_i + \text{FE}_t + \varepsilon$$

For each of the three measures of embeddedness (1–3), we estimate three models (a–c). Model a includes 99 countries for which network and policy variables are available. Models b and c include only the 18 OECD countries for which *installed PV capacity* and *PV R&D expenditures* are available.[11] Model b estimates model a for the smaller OECD sample

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

[10] As explained in Section 3.2, networks are reconstructed for overlapping three-year moving windows. A lag of three years leads to no overlap between different networks.

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

Table 4
OLS-panel regression results for country embeddedness, periods 1980–1982 until 2013–2015.

	Degree			Flow betweenness			k-Core		
	Model 1a	Model 1b	Model 1c	Model 2a	Model 2b	Model 2c	Model 3a	Model 3b	Model 3c
Mean Strength$_{t-3}$	2.186***	0.379	0.562	642.310**	360.226	388.130	0.744***	−0.030	−0.044
	(0.541)	(0.541)	(0.522)	(270.417)	(484.992)	(427.864)	(0.171)	(0.123)	(0.130)
Degree Centralization$_{t-3}$	−18.509***	−16.209***	−10.336**	−6372.334***	−10153.781*	−6027.097	−2.425*	1.873	0.920
	(2.919)	(5.300)	(4.392)	(1655.650)	(5216.224)	(3805.733)	(1.256)	(1.435)	(1.373)
Share in Main Component$_{t-3}$	10.010***	9.517***	5.315	2651.762***	3042.337*	157.752	0.680	−0.512	0.178
	(2.436)	(2.436)	(3.763)	(926.439)	(1682.146)	(1838.029)	(0.793)	(0.631)	(0.751)
Kyoto Ratification$_{t-1}$	0.618	2.715***	2.741**	−347.436	−578.118	−4.880	−0.024	−0.701	−0.782
	(1.033)	(0.914)	(1.375)	(533.444)	(1299.025)	(766.470)	(0.327)	(0.600)	(0.543)
Cum. Number of Satellites$_{t-1}$	0.019***	0.016***	0.016***	14.098***	13.336***	14.168***	0.000	−0.002*	−0.002**
	(0.004)	(0.003)	(0.003)	(2.352)	(2.480)	(2.003)	(0.002)	(0.001)	(0.001)
Installed PV Capacity$_{t-1}$			1.284**			882.222***			−0.209**
			(0.581)			(313.398)			(0.089)
PV R&D Exp.$_{t-1}$			−0.018*			15.605**			0.000
			(0.010)			(6.336)			(0.001)
PV R&D Exp. interp. Dummy$_{t-1}$			−0.575			−294.517			−0.142
			(1.444)			(1149.031)			(0.146)
GDP per Capita$_{t-1}$	0.000**	0.000	0.000	0.029	−0.128	−0.093	0.000**	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.035)	(0.123)	(0.085)	(0.000)	(0.000)	(0.000)
EU Membership$_{t-1}$	−0.990	0.551	0.714	−1071.045***	619.309	1129.039**	0.625	−0.114	−0.183
	(1.635)	(2.199)	(1.941)	(394.676)	(841.276)	(537.511)	(0.716)	(0.540)	(0.498)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adj. R^2 (within)	0.305	0.148	0.230	0.252	0.229	0.345	0.059	−0.005	0.030
n	99	18	18	99	18	18	99	18	18
T	34	34	34	34	34	34	34	34	34
Obs.	1540	437	437	1540	437	437	1540	437	437
df	1401	379	376	1401	379	376	1401	379	376

Robust standard errors in parentheses.
* Sig. at 0.1 level.
** Sig. at 0.05 level.
*** Sig. at 0.01 level.

to see if differences in coefficients between models a and c are due to the inclusion of additional variables or because of the smaller sample.

4.3. Results

With three dependent variables and three specifications, we end up with nine regression models to analyze the effects of national network structure and policy intervention (Table 4). In the following, we discuss the results for the three different measures of embeddedness separately, followed by an overall summary of the results.

4.3.1. Degree

The factors influencing international embeddedness as measured by a country's *degree* are estimated in models 1a-c. In model 1a, the three national network measures show significant effects in the expected direction. With respect to the policy variables, there is an effect from procurement proxied by the *cumulated number of satellites* but not by the *Kyoto Ratification*, which accounts for an overall commitment to mitigate climate change. If the sample is reduced to the 18 OECD countries, there is a significant effect of the *Kyoto Ratification* but *mean strength* does not play a role. After including additional policy variables in model 1c, the effect of *share in main component* is not significant anymore. With respect to the additional policy variables, *installed PV capacity* positively influences embeddedness while, surprisingly, *PV R&D expenditures* have a significant negative effect.

4.3.2. Flow betweenness

Flow betweenness is analyzed in models 2a-c. In model 2a, the results are similar to model 1a for *degree*, with differences only in the controls. If the number of countries is reduced to the OECD sample in model 2b, *mean strength* is again no longer significant. The additional policy variables in model 2c result in a loss of significance of the national network measures as well. As above, *installed PV capacity* is positive, and, contrary to *degree*, *PV R&D expenditures* have a positive significant effect.

4.3.3. k-Core

In the case of *k-core*, model 3a reveals that only national collaboration in terms of *mean strength* and *degree centralization* have a significant influence on membership in a higher level core of the global knowledge network. The models 3b and 3c show opposite signs for *cumulated number of satellites* and *installed PV capacity* and none of the other variables are significant. 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 OECD countries included in the two models enter the core at some point, so that there is very little variation in the dependent variable (see Fig. 6). As such, this measure of embeddedness 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. We therefore abstain from interpreting the models 2b and 2c in the following.

4.3.4. Summary

Overall, international embeddedness in the global research network is 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. However, this holds true only for models that include the large set of countries, regardless of how embeddedness is measured. For the models that cover only 18 OECD countries, this relationship does not hold. Centralization of the national research system is detrimental for embeddedness and H 2 gains support in all models with the large country sample and also for *degree* and partly for *flow betweenness* in the OECD sample. This indicates that countries with centralized PV research activity and a focus on 'national champions' are on average 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* model as well as in the *flow betweenness* for the large sample of countries and partly in *degree* and *flow betweenness* for the OECD sample. In general, the national network structure seems to be a good predictor of international embeddedness, especially if a larger population of countries is considered and in the absence of additional policy variables.

With respect to the influence of governmental intervention, H 4 assumes that direct R&D subsidies increase embeddedness. However, our results are inconclusive. There is a negative effect if embeddedness is measured by *degree* and a positive effect on *flow betweenness*. Apparently, research funds are not used to establish new connections per se, but to establish or intensify connections to well embedded countries. In line with H 5, demand side policies have a very robust positive effect on embeddedness. This holds for demand side policies as proxied by *installed PV capacity* and also for public procurement as proxied by the *cumulated number of satellites*. 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 hypothesis is only supported in the *degree* models for the 18 OECD countries. This might be explained by the differential binding effect of the Kyoto Protocol. In the whole sample, many developing or less developed countries signed the Kyoto Protocol without having to commit to emission reductions, whereas for the 18 OECD countries, it unfolds its binding effect. While, overall, governmental interventions influence international embeddedness, the instruments differ in their effects. Market creation 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 two robustness tests for the econometric analysis. First, we deal with the less reliable publication data in early years by analyzing a subset for later periods only. Second, we use the number of *publications* as a measure for the overall research output. Publications are the underlying data for the networks so that it serves as a benchmark for the regressions on international embeddedness.

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 8, 10, and Table 11 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. There are only two changes worth discussing: In Model 1c, the *share in main component* becomes significant and in Model 2c *degree centralization* as well. Both differences strengthen our argument with respect to the importance of the national network structure. Since the networks in early periods are very small and sparse, they are a less reliable indicator of research system structure.

Our measures of embeddedness are based on the co-authorship of scientific publications. As such, countries can only be embedded in the international research network if they publish research articles. We therefore perform the same regressions as above on the number of publications[12] to find out whether the effects of policies differ between embeddedness and research output (see Table 5). Without any difference, embeddedness would merely be a side-effect of increased output. Overall, the results do not differ much. Characteristics of the research system, especially *mean strength* and *degree centralization*, as well as the technology push and demand pull policies influence both, embeddedness and output. However, there are also some noteworthy differences that make us confident that certain policies and system characteristics are relatively more important for embeddedness than for publication output. The functionality of the research system as measured by the *share in main component* seems irrelevant for the number of publications but not for embeddedness. *Kyoto Ratification* increases the number of international partners but has no influence on the number of publications. This indicates that acknowledging greenhouse gas emissions as a global societal problem induces international collaboration.

Table 5
OLS-panel regression results for country publications, years 1980–2013.

	Publications		
	Model 4a	Model 4b	Model 4c
Mean Strength$_{t-3}$	71.778***	33.643	34.000**
	(18.964)	(21.388)	(16.872)
Degree Centralization$_{t-3}$	−400.025***	−493.474***	−347.866***
	(76.716)	(164.580)	(102.799)
Share in Main Component$_{t-3}$	50.452	95.843	−11.818
	(36.195)	(94.653)	(95.295)
Kyoto Ratification$_{t-1}$	−31.847	−82.040	−49.425
	(29.124)	(82.440)	(45.677)
Cum. Number of Satellites$_{t-1}$	0.947***	0.901***	0.962***
	(0.191)	(0.105)	(0.054)
Installed PV Capacity$_{t-1}$			30.850**
			(14.065)
PV R&D Exp.$_{t-1}$			1.253***
			(0.277)
PV R&D Exp. interp. Dummy$_{t-1}$			−51.828
			(59.005)
GDP per Capita$_{t-1}$	−0.002	−0.009	−0.007
	(0.002)	(0.006)	(0.005)
EU Membership$_{t-1}$	−56.518***	−0.247	7.973
	(20.382)	(35.980)	(23.693)
Country fixed effects	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
Adj. R^2 (within)	0.307	0.415	0.521
n	97	18	18
T	34	34	34
Obs.	1413	421	421
df	1276	363	360

Robust standard errors in parentheses. * Sig. at 0.1 level.
** Sig. at 0.05 level.
*** Sig. at 0.01 level.

5. Discussion and conclusion

In the present study we analyzed the global research network in PV based on an original dataset of scientific publications to describe its evolution between 1980 and 2015 and to identify the determinants of a country's embeddedness in the international research network. Regarding the determinants of embeddedness, we derived a set of hypotheses on the influence of characteristics of the national research system and instruments of the policy mix for renewable energies and tested them for a large sample of countries.

With respect to the evolution of structural properties of the global PV research network, we observe that research output and the resulting

[12] Since we use this specification to check the robustness of our results, rather than to measure research performance, we abstract from using citation-weighted publication shares, or similarly, more sophisticated measures of scientific performance.

network of international research collaboration are constantly growing. As such, we observe a process of globalization of the research network as a key component of the global PV innovation system (Binz and Truffer, 2017). This reflects 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 catch up and overtake European countries in terms of research output, indicating that the increase in PV production during recent years (Zheng and Kammen, 2014) goes hand in hand with increased research activities. We also observe an increase in collaboration over time, which is not specific to PV but a general trend in research and innovation activities (Wuchty et al., 2007; Adams, 2012). 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 (Luukkonen et al., 1992). There is not only a surge in research output, but also in terms of the number of actors, which indicates that an increasing number of countries engage in PV research. The reasons should be found in environmental awareness as well as improved market opportunities and industrial policies (Stern, 2007; Mazzucato, 2013).

Countries that engage in PV research are quickly embedded in the global research network and the number of connections per actor increases steadily. Thereby, the network becomes increasingly connected, suggesting that the global system functions well and allows for knowledge diffusion. However, there seems to be an ongoing centralization process, such that some countries form a highly interconnected core, which has also been found for other fields (Leydesdorff and Wagner, 2008). The network periphery is characterized by a substantial degree of turbulence. Some countries, such as Mexico, Russia, and the Netherlands, move towards the network periphery, despite a doubling of their number of connections. Others improved their relative position in the network, especially countries in the MENA region due to strategic decisions taken by their governments (Griffiths, 2013). Also Malaysia, which only recently engaged in PV research due to overall political commitment, moved among the top countries (Muhammad-Sukki et al., 2012). The increase in centrality of some Asian countries, especially China, Taiwan, South Korea, and India, is fairly moderate. Even though they nowadays publish most of the research in PV, they are not among the most central countries. As such, by giving priority to national partnerships, they do not fully exploit their knowledge sourcing potentials.

In the regressions, embeddedness is measured by three concepts of network centrality that emphasize different aspects of knowledge access. If measured by the number of collaborating countries (degree), as well as the relative position and intensity of collaboration (flow betweenness), the results are by and large in line with our hypotheses. Membership in a highly connected core, as measured by k-core, shows to be a less convincing measure of embeddedness. To explore the determinants of international embeddedness, we employ two sets of country characteristics.

With the first set of factors, we enter an emerging research field by relating country level network characteristics – the meso level – to macro level embeddedness (Dopfer et al., 2004; Gupta et al., 2007). While there are some studies concerned with the effects of network structure on performance (e.g. Verspagen and Duysters, 2004; Uzzi et al., 2007; Fritsch and Graf, 2011), only a few studies relate different levels of networks in a research or innovation context (Gupta et al., 2007; Paruchuri, 2010; Guan et al., 2015b). 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 (Carlsson and Stankiewicz, 1991; Lundvall, 1992; Smits and Kuhlmann, 2004; Hekkert et al., 2007). The results are – at least partly – sensitive to the centrality concept used to measure embeddedness. Cohesion and connectedness of the national network positively influence international embeddedness. However, the effects are not as pronounced for the sample of 18 OECD countries for which policy variables are available. These countries have a long tradition of collaboration on economic and innovation related topics so that it can be well assumed that their research systems converged during the past decades. All are industrialized countries with strong and functioning research systems that emphasize national and international collaboration (OECD, 2010, 2014). Centralization of the national network, i.e. a focus on 'national champions', shows to be detrimental for embeddedness. This implies that diffusion oriented research systems in which actors are well connected, diverse, and decentralized are supportive of international embeddedness. However, the establishment of an institutional systems conducive for such structures is certainly influenced by policy intervention and strategic decisions of governments (Ergas, 1987). Overall, our empirical results show that country level network structures are highly relevant for international embeddedness. However, one has to bear in mind that the link between policies in terms of the system setup and their effects is not immediate. Rather, it should be thought of as a process of institutional change that is path dependent, non-linear, and not easily reproducible because of its interactions with other national norms, culture, and institutions (Freeman, 1995, 2002). While the innovation system approach has always put great emphasis on learning, interaction, and the institutional setup (Soete et al., 2010), it has often merely been applied as a focusing device when performing comparative case studies with a lack of guidance with respect to the operationalization of some of its core concepts in broader empirical studies. Our contribution in that respect is to link some core characteristics of innovation systems to structural network properties and to show the relevance of these properties for performance aspects of innovation systems.

The second set of factors is comprised of national policies towards PV and climate change, implemented to fix market failures (e.g. Rennings, 2000; Jaffe et al., 2005). Thereby, we 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). Our results indicate that policy instruments have a differential effect on international embeddedness. R&D expenditures for PV are the most direct way to support research activity (Adams et al., 2005; Popp, 2016) and international cooperation (Adams et al., 2005; Ebadi and Schiffauerova, 2013). Our results for R&D expenditures are mixed and sensitive to measure of embeddedness. They show a negative effect on the embeddedness in terms of degree, but have a positive effect if the relative position of countries in the network is considered. This implies that R&D expenditures are used to establish or intensify connections to well embedded countries rather than to establish connections to previously unrelated countries. In addition, there might be an indirect effect of R&D expenditures on international embeddedness. Since R&D grants have been found to increase collaboration within the country (Adams et al., 2005; Cantner et al., 2016), they help to establish a structure of the national research network that is conducive to international collaboration. Demand pull policies are a very robust predictor of international embeddedness. Even though they are not designed to foster international R&D and collaboration, they apparently provide incentives and create an environment that strengthens international research activities. In addition to market creating demand pull instruments, such as quotas or feed-in-tariffs, we also analyzed the effects of public procurement, which is highly relevant for innovative activity (Edler and Georghiou, 2007; Guerzoni and Raiteri, 2015). 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. This hints 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). The commitment to mitigate climate change indicated by ratifying the Kyoto Protocol seems only to increase the number of international cooperations for the sample of 18 OECD countries. This seems reasonable, since these countries have binding reduction targets, whereas, in the whole sample, many countries do not need to reduce their emissions. Overall, policy instruments have an effect on international embeddedness and knowledge exchange, which has so far been neglected from discussions about an effective policy mix (Flanagan et al., 2011; Rogge and Reichardt, 2016).

Based on these results, we recommend policy makers to consider the following propositions. First, the general setup of the national research system should be higher on the policy maker's agenda to secure integration in international research communities and to embed a country in such networks. There has been discussions about systemic instruments that support functions of a research system (Smits and Kuhlmann, 2004; Hekkert et al., 2007; Wieczorek and Hekkert, 2012). These instruments can be used to create a diffusion oriented research system and embed countries in international networks. This seems to be especially relevant for countries that are developing their research capacity. Steering the research system into a diffusion oriented would increase the collaboration with international researchers. Second, policy instruments that are supposed to increase research activity also increase collaboration and international embeddedness. These partially unintended effects should be taken into consideration by policy makers and fostered to increase the effect of instruments. A striking example is the EU-Framework program, which encourages international collaboration and increase access to global knowledge flows. In a same vein, a well-tailored mix of different instruments should be implemented to not only increase research performance, but also support access to international knowledge flows. Thereby, the policy support should include (pre-)commercial support as well as classical R&D support.

This study contributes to several streams of research. First, a novel approach to measure the functionality of a research system is proposed and used to understand how the design of the research system influences global connectivity. While we treat the drivers of the national research network setup as a black box, we encourage further research to understand how this is shaped, for example, deliberately by systemic instruments (Smits and Kuhlmann, 2004; Wieczorek and Hekkert, 2012; Cantner et al., 2016). Second, by making use of the multi-level structure of publication data in our analysis, we contribute to the emerging stream of research on multi-level networks (Gupta et al., 2007). We show that the meso level influences structures on the macro level, as proposed in theoretical discussions (Dopfer et al., 2004). Third, we provide novel insights into how actor's embeddedness in a network is influenced. We operationalize embeddedness in three different ways and use several possible determinants that extend the determinants that have previously been used (Wanzenböck et al., 2014, 2015). Lastly, with respect to the effect of different innovation policy instruments, we show that these instruments not only increase research activity, but also positively affect international collaboration and embeddedness. This dimension has so far been neglected in the discussion of the effect of different policy instruments. Thereby, we add public procurement to the already established set of instruments and extend the discussion about the composition of the instrument mix for renewable energies (Flanagan et al., 2011; Rogge and Reichardt, 2016).

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 are 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), or Glänzel and Schubert (2005). 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 scope of data coverage would increase the reliability of our results. Finally, since we focus on a highly specific technology in which policy plays an important role, 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 broader policy mix to affect network structures. This would require a deeper look at the policy strategies and goals as well as the consistency and stringency of the mix (Rogge and Reichardt, 2016). Another issue regards the interplay between meso structure and macro embeddedness. Here, we assumed that this is a one-directional relationship where the meso influences the macro. However, there might well be a reverse link so that macro embeddedness influences the way linkages on the meso level are formed. A thorough analysis of these feedbacks and interdependencies remains another challenge for future inquiry.

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Appendix

Table 6
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 7
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

Table 8
Descriptive statistics of the periods 1997–1999 until 2013–2015.

	Min.	Median	Mean	Max.	SD	Obs.
Dependent variables						
Degree_t	0.000	11.000	16.535	87.000	16.219	1231
$\text{Flow Betweenness}_t$	0.000	336.000	1498.846	45,521.000	3640.156	1231
K-Core_t	0.000	9.000	9.717	27.000	7.035	1231
National network variables						
$\text{Mean Strength}_{t-3}$	0.000	1.000	1.490	16.264	1.716	1231
$\text{Degree Centralization}_{t-3}$	0.000	0.133	0.134	0.667	0.113	1231
$\text{Share in Main Component}_{t-3}$	0.060	0.475	0.462	1.000	0.218	1231
National policy variables						
$\text{Kyoto Ratification}_{t-1}$	0.000	1.000	0.636	1.000	0.481	1231
$\text{Cum. Number of Satellites}_{t-1}$	0.000	0.000	76.253	3412.000	426.535	1231
$\text{Installed PV Capacity}_{t-1}$	0.000	1.423	2.331	9.138	2.442	284
$\text{PV R\&D Exp.}_{t-1}$	0.000	8.239	24.297	395.660	43.405	284
$\text{PV R\&D Exp. interp. Dummy}_{t-1}$	0.000	0.000	0.092	1.000	0.289	284
Controls						
$\text{GDP per Capita}_{t-1}$	428.150	15,585.486	20,702.082	164,136.454	17,460.171	1231
$\text{EU Membership}_{t-1}$	0.000	0.000	0.265	1.000	0.441	1231

Table 9
Correlation table for the periods 1980–1982 until 2013–2015.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Degree_t	1.000													
2	$\text{Flow Betweenness}_t$	0.782	1.000												
3	K-Core_t	0.873	0.580	1.000											
4	Publication_t	0.598	0.824	0.425	1.000										
5	$\text{Mean Strength}_{t-3}$	0.707	0.576	0.663	0.599	1.000									
6	$\text{Degree Centralization}_{t-3}$	0.352	0.178	0.447	0.149	0.566	1.000								
7	$\text{Share in Main Component}_{t-3}$	0.206	0.242	0.190	0.279	0.503	0.435	1.000							
8	$\text{Kyoto Ratification}_{t-1}$	0.385	0.210	0.543	0.103	0.296	0.300	0.227	1.000						
9	$\text{Cum. Number of Satellites}_{t-1}$	0.196	0.180	0.094	0.178	0.094	0.105	−0.034	−0.088	1.000					
10	$\text{Installed PV Capacity}_{t-1}$	0.834	0.758	0.744	0.675	0.666	0.269	0.530	0.528	0.124	1.000				
11	$\text{PV R\&D Exp.}_{t-1}$	0.214	0.356	0.010	0.503	0.198	−0.111	0.002	−0.130	0.635	0.254	1.000			
12	$\text{PV R\&D Exp. interp. Dummy}_{t-1}$	0.131	0.089	0.106	0.093	0.143	0.073	0.132	0.025	0.161	0.096	−0.019	1.000		
13	$\text{GDP per Capita}_{t-1}$	0.446	0.280	0.405	0.180	0.311	0.150	0.045	0.128	0.067	0.380	0.125	0.107	1.000	
14	$\text{EU Membership}_{t-1}$	0.298	0.144	0.234	−0.004	0.139	0.121	0.010	0.069	−0.110	−0.002	−0.254	−0.012	0.324	1.000

Table 10
Correlation table for the periods 1997–1999 until 2013–2015.

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Degree_t	1.000												
2	$\text{Flow Betweenness}_t$	0.787	1.000											
3	K-Core_t	0.859	0.573	1.000										
4	$\text{Mean Strength}_{t-3}$	0.682	0.561	0.628	1.000									
5	$\text{Degree Centralization}_{t-3}$	0.288	0.139	0.378	0.530	1.000								
6	$\text{Share in Main Component}_{t-3}$	0.178	0.235	0.122	0.515	0.446	1.000							
7	$\text{Kyoto Ratification}_{t-1}$	0.265	0.143	0.411	0.184	0.186	0.141	1.000						
8	$\text{Cum. Number of Satellites}_{t-1}$	0.229	0.210	0.126	0.119	0.142	0.021	−0.091	1.000					
9	$\text{Installed PV Capacity}_{t-1}$	0.810	0.724	0.676	0.561	0.050	0.466	0.363	0.182	1.000				
10	$\text{PV R\&D Exp.}_{t-1}$	0.485	0.559	0.183	0.381	−0.121	0.258	−0.114	0.668	0.466	1.000			
11	$\text{PV R\&D Exp. interp. Dummy}_{t-1}$	0.094	0.062	0.046	0.118	0.062	0.094	−0.050	0.229	0.054	0.030	1.000		
12	$\text{GDP per Capita}_{t-1}$	0.451	0.281	0.422	0.307	0.123	0.077	0.106	0.051	0.202	0.208	0.088	1.000	
13	$\text{EU Membership}_{t-1}$	0.379	0.180	0.335	0.186	0.151	0.067	0.140	−0.095	−0.026	−0.258	−0.032	0.339	1.000

Table 11
OLS-panel regression results for country embeddedness, periods 1997–1999 until 2013–2015.

	Degree			Flow betwenness			k-Core		
	Model 1a	Model 1b	Model 1c	Model 2a	Model 2b	Model 2c	Model 3a	Model 3b	Model 3c
$\text{Mean Strength}_{t-3}$	2.183***	−0.066	0.117	667.201***	288.217	451.481	0.726***	−0.051	−0.132
	(0.416)	(0.322)	(0.308)	(256.654)	(410.184)	(419.523)	(0.152)	(0.157)	(0.168)
$\text{Degree Centralization}_{t-3}$	−14.106***	−12.199***	−10.821**	−5142.913***	−11189.149**	−9478.380**	−2.923**	1.691	0.984
	(2.566)	(4.432)	(4.437)	(1463.247)	(5421.651)	(4630.801)	(1.300)	(1.468)	(1.314)
$\text{Share in Main Component}_{t-3}$	6.440***	8.402***	6.439**	1977.474**	3423.751**	1604.725	0.205	−0.352	0.538
	(1.979)	(2.629)	(2.655)	(821.927)	(1645.123)	(1646.171)	(0.766)	(0.769)	(0.920)
$\text{Kyoto Ratification}_{t-1}$	−0.064	1.656*	1.669*	−211.367	1335.970	1299.211	−0.139	−0.956	−0.956*
	(0.766)	(0.898)	(1.001)	(380.121)	(1034.839)	(1093.581)	(0.380)	(0.584)	(0.543)
$\text{Cum. Number of Satellites}_{t-1}$	0.028***	0.013***	0.012**	44.798***	48.245***	41.705***	0.002	−0.004**	−0.002**
	(0.011)	(0.004)	(0.005)	(12.501)	(3.217)	(4.060)	(0.003)	(0.002)	(0.001)
$\text{Installed PV Capacity}_{t-1}$			0.620**			525.582*			−0.271**
			(0.263)			(273.996)			(0.110)
$\text{PV R\&D Exp.}_{t-1}$			−0.012***			15.812**			0.000
			(0.004)			(6.843)			(0.001)
$\text{PV R\&D Exp. interp. Dummy}_{t-1}$			0.237			−416.041			−0.032
			(1.253)			(1573.139)			(0.223)
$\text{GDP per Capita}_{t-1}$	0.000	0.000	0.000	0.002	−0.115	−0.086	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.034)	(0.100)	(0.083)	(0.000)	(0.000)	(0.000)
$\text{EU Membership}_{t-1}$	−1.881			−1020.279***			0.425		
	(1.877)			(333.918)			(0.843)		
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adj. R^2 (within)	0.216	−0.002	0.028	0.293	0.348	0.388	0.013	0.013	0.066
n	99	18	18	99	18	18	99	18	18
T	17	17	17	17	17	17	17	17	17
Obs.	1231	284	284	1231	284	284	1231	284	284
df	1109	244	241	1109	244	241	1109	244	241

Robust standard errors in parentheses.
* Sig. at 0.1 level.
** Sig. at 0.05 level.
*** Sig. at 0.01 level.

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