WHERE ARE THE ECO-INNOVATORS? ANALYSIS OF THE KNOWLEDGE FLOWS BETWEEN SUCCESSIVE GENERATIONS OF GREEN TECHNOLOGY INNOVATIONS

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ABSTRACT

This paper examines the location of innovations within green technology, using U.S. patent citation data to trace their inter-generational knowledge flows over time. Clustering is clearly evident, and we use multivariate left-censored Tobit regression analysis to control for identifiable factors, to show that the distance between successive innovators has not been rising over time. The interesting exception is nuclear energy in which distance appears to be decreasing over time. If we consider only inter-city transfers, the waste management also becomes more concentrated over time, while transportation declusters.

1. INTRODUCTION

Firms within an industry often cluster geographically due to localization benefits that reduce the cost of inputs to firms in the local industry [1,2], due to the rapid speed of knowledge diffusion [3] or due to tacit learning advantages [4]. To our knowledge no analysis has tested the importance of these clustering forces within green technologies, nor traced its impact across time.

Using all green technology patents granted in the U.S. between 1976 and 2002, we statistically test whether there has been a trend to cite knowledge arriving from greater distances, and whether such a pattern could arise from (or be abated by) a tendency to cite other patents listing the same inventor, the same firm assignee, or the same technology class. We conclude that the geographic clustering of citations holds over and above the effects of these other factors, suggesting that there is a local nature to knowledge spillovers (at least insofar as patent citations reflect knowledge flows), and that this tendency is not weakening over time.

As Figure 1 shows, the average distance between a citing patent and its bibliographic references differs by the type of green technology considered, and may have grown slightly between 1976 and 2002. The multivariate regression which follows controls for other changing factors, but the same fundamental pattern remains.

![Fig 1. Average citation distance in kilometers](image)

In section 2 of the paper, we briefly review the relevant literature on technology clustering and the geographic nature of knowledge spillovers. Section 3 describes our data set, designed for compatibility with the literature, and Section 4 presents multivariate regression analysis that controls for non-geographic effects in presenting the role of distance. Section 5 concludes with implications for policy and further research.

2. LITERATURE REVIEW

Most technical and economics literature indicates that knowledge transfers more readily across short distances. The underlying supposition is that inventors are more aware of (or find more use for) inventions located close to them, and therefore build more heavily on local inventions.

Empirical evidence confirms the role of location in the spillover of knowledge from one member of an innovation network to another [5], but some research points out that the
importance may differ by technology [6] with location more important for technologies undergoing radical innovation. During technological revolutions, such as some fields of green technology experienced in the period under study, we might reasonably expect some large geographic impacts on knowledge flows.

R&D-intensive activities have been effectively explained using geographic proximity [7], but the location of firms is not always a good indicator of the location of innovation [8,9]. It has been firmly established that patents are more likely to cite local patents than patents by parties that are located farther away [10-14], an effect especially prevalent in electronics, optics, and nuclear technology [15]. However, none of these studies examined how that importance has changed over time.

However, there are studies suggesting that distance has never mattered much [16], or that there has been little change over time, even with revolutionary changes in information and communication technology [17,18].

3. DATA

Every patent application must include citations to any other patents essential to its creation, or which limit its legal breadth. Inventors create this citation list to prove the novelty of the patentable product or process, and the result is a paper trail of knowledge creation. Of course, patents records do not measure innovation perfectly, as some inventions are never patented and patents vary greatly in importance. However, patents have a high correlation with the location of other measures of innovative activity [8]. While citations do not perfectly reflect the transfer of knowledge, as they may be inserted for a variety of reasons, evidence shows that half show true knowledge transfer [18], and if the noisiness of this signal is constant over time, we can use it to compare time periods even with an implied degree of imprecision.

We follow the World Intellectual Property Organization’s definition for green technology [19], and our dataset therefore includes all patents granted between 1976 and 2002 that qualify as green technology, appended with all patents cited by those patents, at least those that were themselves granted between 1976 and 2002. Citing and cited patents from all non-U.S. inventors have been excluded, for reasons of feasibility. However, there is evidence in the literature that international citations are increasing in frequency across a host of technologies [20].

Patent citations may cluster for non-geographic reasons, causing a pattern that appears geographic. For example, inventors (or the assignees firms which retain patent rights) may be more familiar with their own patents, citing them frequently, a pattern which would give a biased impression of the importance of geography. Therefore we include self-citations in the analysis but identify and control for them separately.

Using U.S. patent data from a combination of sources (NBER website as described in [21], in addition to raw data collected by the independent firm MicroPatent), each patent citation’s endpoints (citing patent and cited patent) were geo-coded for the primary location of each listed U.S.-based innovator. We identified locations at the geographic center of the city, as specific street addresses are available for less than ten percent of all patent documents.

The result is a dataset of 299,147 citations from U.S.-based green technology patent documents to other U.S.-based patent documents. Previous literature [13,14] indicates that each of the following factors may play some role in the distance of a citation, so this research measured each for every observed citation between citing patent K and cited patent k:

- whether they have the same inventor (hereafter, SI);
- whether they have the same assignee (SA);
- whether they are in the same technology (ST);
- how similar the citing and cited states are in technology types (SC);
- whether the cited patent is also classified as eco-innovation or green technology (E);
- whether the assignee is a government agency (G);
- whether the assignee is an educational institution (U);
- how old the citation is, in years between citing and cited patent (A), along with its squared term (A^2) to account for the potentially nonlinear effects of age;
- and a time trend variable to proxy for the year of citation (T), along with its squared term (T^2).

First, we traced all self-citations, allowing for some flexibility in name spellings (since the United States Patent and Trademark Office, or USPTO, does not standardize name format). These include not only first inventors, but all inventors listed for each patent. Self-citation by inventors accounted for between one and ten percent of all citations, depending on the subsector (with alternative energy technologies showing the most self-citations, and most technologies hovering around three to five percent). This suggests that while some self-citation is present, there are very strong inter-inventor knowledge spillovers. Self-citation by assignees was much more frequent, ranging between seventeen and thirty-five percent of all citations (highest in the nuclear energy sector), much higher than found in other sectors like biotechnology [13] and traditional energy [14], suggesting that knowledge transfers between individuals or firms are less frequent in green technology. Unlike academic citations, there is very little reason here to self-cite as a means of advertising, so we can be fairly sure that self-citations are indicators of useful capital or legal protection. Self-citation was coded as a binary variable (SI) for each citation.
It is also possible that patents closer in technological content may cite each other more frequently, regardless of location. The data are coded so that a binary variable, ST, indicates whether the International Patent Classification (IPC) system places both citing and cited patents in the same technology cluster at the 4-digit level. This system [19], in global use since 1975, is the standard by which all patents are organized (and thus assigned to examiners for processing, or searched by inventors and lawyers to establish claims). There are 634 clusters at the 4-digit level, so an indicator that the patents share a class is a powerful signal of technological similarity, and a strong indicator that they were both processed by patent examiners with very similar scientific training. In our sample, roughly half of all citations saw citing and cited patents sharing a technology class.

The technological correlation between citing and cited states (SC), is included for a similar reason. Each state’s technological profile was calculated as the share of patent activity assigned to each of the 634 IPC technology classes. Pair-wise correlations between state vectors then provide a measure of technological similarity between locations. Controlling for technological similarity between locations will defuse the ability of the data to show an importance of geography that may be superficially the result of two regions sharing the same technological portfolio and hence attracting citation flows. Our sample shows an average correlation of 0.85 between cited and citing state technology profiles.

The analysis also includes an indicator of whether the cited patent is classified as green technology (E). Obviously, all citing patents have been defined as such, and there should be a higher probability for them to cite other green technology patents than to cite a random other technology group. There is great variation here between subsectors, with the nuclear sector making two-thirds of its citations to other green technologies, while the administrative sector cites green technologies only one-quarter of the time.

Because government (G) and university (U) patents may cite knowledge differently than do private sector patents, we include those indicators as controls as well, but only one to five percent of patents within each subsector qualify in either category.

Linear and squared age terms are included to accommodate nonlinear effects for older knowledge. The average citation is just roughly 7 years from cited to citing document.

Finally, since the goal of the analysis is to test whether distance changes over time, it is necessary to a time trend (and its square, to permit nonlinearities) or to include indicator variables for each time period.

To permit different subsectors of green technology to reflect their own unique patterns, we have divided the sector into six distinct and mutually exclusive subsectors: Administration & Design, Alternative Energy (including biofuels, fuel cells, solar, wind and geothermal), Energy Conservation, Nuclear Power, Transportation and Waste Management.

4. STATISTICAL ANALYSIS

Our regression analysis follows the literature [13,14] in using a simple model [22] with the citation as the unit of analysis. We model the distance between a cited patent k granted in year t and a subsequent citing patent K granted in year T, explaining it as a function of the attributes of patents k and K:

$$\delta_{k,K} = \alpha(k,K) + \varepsilon$$

where $\delta_{k,K}$ represents the distance between patents k and K, $\alpha(k,K)$ is a vector of the non-geographic attributes of patents k and K that affect the probability of citation, and $\varepsilon$ is a randomly distributed error term. We propose a reduced functional form, using the log of distance (or technically the log of [distance plus one]) in order to avoid taking the log of a zero distance) because the fit of the equation is better due to the loglinear nature of the data’s underlying relationship:

$$\delta_{k,K} = \alpha_0 + \alpha_{SA}ST + \alpha_{SI}SI + \alpha_{SC}SC + \alpha_{E}E$$

$$+ \alpha_{G}G + \alpha_{U}U + \alpha_{T}T + \alpha_{A}A + \alpha_{T}T^2 + \varepsilon_k$$

where the distance $\delta$ of each observed citation is explained by the attributes of the citing and cited patents as defined above. Notice that we use a fixed effect specific to the citing patent ($\varepsilon_k$), since there are presumably immeasurable factors specific to the citing patent which might dictate a longer or shorter average citation distance.

Table 1 presents multivariate regression Tobit estimates (left-censored for intra-city citations with a distance of 0 miles), with White-corrected errors to accommodate the presence of heteroskedasticity in the sample, using fixed effects at the level of the citing patent where each individual citations is the unit of analysis. For simplicity, we estimate using only a time trend (and its square) to measure the change due to the passage of time, after other factors have been controlled. In most cases the trend coefficient is insignificant, indicating a lack of evidence that average distance either increases or decreases with time, ceteris paribus. These results are confirmed when considering only inter-city citations (or citations with distances greater than 100 kilometers, shown in Table 2).

The one exception to this pattern is nuclear energy, where the trend coefficient is insignificant, indicating a lack of evidence that average distance either increases or decreases with time, ceteris paribus. These results are confirmed when considering only inter-city citations (or citations with distances greater than 100 kilometers, shown in Table 2), notice that the waste management subsector now mimics...
nuclear energy, becoming more concentrated over time. In contrast, the transportation sector has become more decentralized or diffused over the period in question.

To permit maximum flexibility to these nonlinearities, and potential nuances in particular years, the same analysis was conducted using separate year indicator variables. In this ancillary analysis (available from the authors), annual indicator variables provide no distinguishable pattern, as again, the majority of coefficients are insignificant.

Turning our attention to other elements of the regression results, we notice that patents in states that have similar technology sets in their innovative profiles tend to be close together, a fact captured by the negative coefficient on that variable.

Unsurprisingly, citations with the same inventor are more likely to be proximate than are other citations. This suggests that within green technology, inventors are not likely to move locations between self-citations. The exception is inter-city nuclear energy knowledge transfers, which represents a case where individuals are apparently mobile, as self-citations increase the average distance of a citation.

Citations to the same assignee uniformly reference citing and cited patents that are closer to each other than patents with different assignees, except for the cases of transportation and waste management in inter-city flows. There is therefore some evidence that firms in these sectors have well-developed knowledge transfer between branches or between home office and their local innovators.

Citations from government-assigned patents tend to travel longer transmission distances for the knowledge they cite, a result that becomes more significant when we consider only long-distance (>100 km) citations. In like manner, academic patents tend to be slightly further than their peers from the business sector as well, however, this effect is only significantly observed among long-distance citations (>100 km). Both of these results have been confirmed elsewhere in the literature [15].

The age of the cited patent matters as well: older citations travel longer distances, presumably because it takes time for knowledge to travel, an effect which other studies [13, 14, 23] have confirmed for an array of technologies. Interestingly, this effect is frequently reversed or not significant among long-distance citations (>100km).

5. CONCLUSIONS

While we are hesitant to draw major conclusions about the nature of technological change in green technology from this work, several themes appear relatively obvious and robust to alternative interpretations of the data.

First, in stark contrast to numerous other sectors, citation distances appear to be neither increasing nor decreasing over time, whether we model those distances simply as a function of time or as a more complicated function of the attributes of the underlying patents. Thus, it appears that knowledge flows between eco-innovators have been relatively unaffected by recent changes in information and communications technology. This conclusion is even more evident in the nuclear energy sector (or in the inter-city flows within waste management) in which citation distances appear to be shrinking.

Second, other factors may contribute to the explanation of why one patent cites another. Self-citation is not frequent, but apparently has a strong effect on patent citations. Similarly, technological similarities across states appear to correlate with more proximate citations.

Future work will aim to split the Alternative Energy subsector into its constituent elements, to determine whether the solar, geothermal, wind, fuel cell, and biofuel subsectors behave differently, and if any emulate the patterns of the nuclear subsector.

Might we learn something important about innovation through the study of patent citations? Insofar as they reveal the paths of knowledge transmission, then we can identify the patterns and key actors in a technology such as green technology. Despite the diffusion seen in other sectors, green technology remains as localized as ever. While this provides some level of stability as firms remain clustered together, it is disappointing that information does not appear to be more widely utilized (in a geographic sense) over time.

At this point, we can only point to the fact that the diffusion of green technology innovation, unlike other well-documented cases, presents no distinguishable change in its historical pattern. For better or worse, recent changes in telecommunications do not appear to have impacted the ability or willingness of eco-innovators to draw inspiration from more distant locations.

References


5. Gelsing, L. (1992) "Innovation and Development of Industrial Networks". National Systems of


### TABLE 1: TOBIT WEIGHTED REgressions ON Log(DISTANCE+1), TIME TRENd

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<th>t-stat</th>
<th>Conservation coef.</th>
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### TABLE 2: TOBIT WEIGHTED REgressions ON Log(DISTANCE+1), TIME TRENd, INTER-CITY (ONLY DISTANCE>100KM)

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