From Science to Technology: Knowledge Flows in the Renewable Energy Sector

David Popp

May 2018

Introduction

- Most evaluations of energy innovation use patent data
  - Examples include Popp (*AER* 2002, *JEEM* 2006), Johnstone *et al*. (*ERE* 2010), Verdolini and Gaelotti (*JEEM* 2011), Dechezleprêtre and Glachant (*ERE* 2014)
    - Results show that energy prices, policies, and scientific opportunities all influence the development of clean energy technologies

- In recent work, I link scientific publication and patent data to evaluate public energy R&D
  - More appropriate outcome measure for early stage R&D
  - Popp (*Nature Energy* 2016) focuses on lags between funding and research outcomes
  - Popp (*Research Policy* 2017) focuses on knowledge flows across institutions

Data

- Both papers combine patent and scientific publication data

- Patent data from Delphion
  - Available from 1991-2011
  - Use patents granted in US
  - Use IPC classes to identify relevant patents for 3 different technologies:
    - Biofuels, Solar Energy, Wind Energy

- Use non-patent literature (NPL) citations to link scientific publications and patents

Data

- Scientific publication data from Thomson Reuters Web of Science
  - Available from 1991-2011
  - Used keyword searches to identify articles in 4 different technologies:
    - Biofuels, Energy Efficiency, Solar Energy, Wind Energy
  - For each technology, articles are counted by year and country:
    - Weighted counts: assigns articles proportionately by the # of countries represented
      - E.g. 2 US authors and 1 Japanese author: 0.67 US, 0.33 Japan

Returns to Energy R&D Over Time

- Popp (*Nature Energy* 2016) focuses on two questions:
  1. How does government R&D affect outcomes of basic research?
     - How long until new publications to appear?
       - Compare to existing empirical literature, which often uses just a single year of energy R&D
     - Linking publication data to citations on U.S. energy patents, how long until these publications cited by a patent?
  2. Do adjustment costs associated with large increases in research funding result in diminishing returns to government R&D?

Returns to Energy R&D Over Time

- Key results:
  - Links between R&D spending and research outcomes
    - One million dollars in additional government R&D funding leads to 1-2 additional publications, but with lags as long as ten years between initial funding and publication

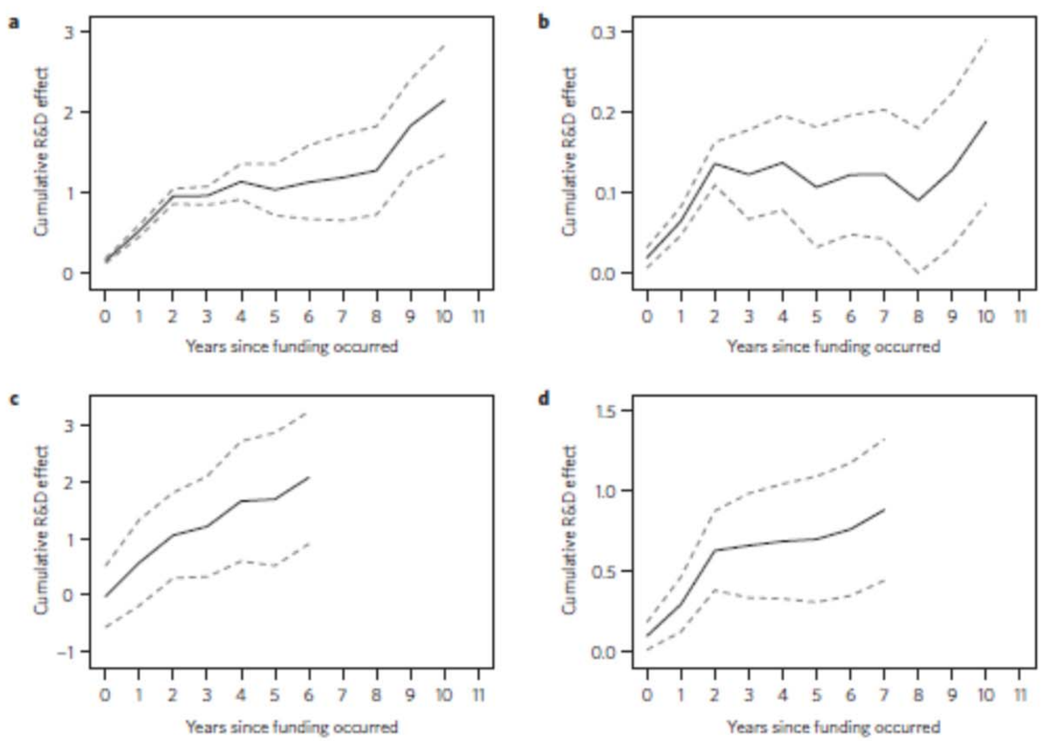


Figure 2 | Cumulative effect of energy R&D on publications. The cumulative effect of an additional US$1 million of public energy R&D on publications through year $t + x$, where x represents years since funding occurred, shown on the x-axis. Dashed lines represent 95% confidence intervals. Biofuels (**a**) energy efficiency (**b**), solar energy (**c**) and wind (**d**).

Returns to Energy R&D Over Time

- Key results:
  - Links between R&D spending and research outcomes
    - One million dollars in additional government R&D funding leads to 1-2 additional publications, but with lags as long as ten years between initial funding and publication
    - Adjustment costs associated with large increases in research funding are of little concern at current levels of public energy R&D support
      - No evidence of diminishing returns for the *quantity* of publications
      - However, using citations as a measure of quality, citations fall as the number of competing publications increases, but magnitude is small

Returns to Energy R&D Over Time

- Key results:
  - Links between R&D spending and research outcomes
    - One million dollars in additional government R&D funding leads to 1-2 additional publications, but with lags as long as ten years between initial funding and publication
    - Adjustment costs associated with large increases in research funding are of little concern at current levels of public energy R&D support
      - No evidence of diminishing returns for the *quantity* of publications
      - However, using citations as a measure of quality, citations fall as the number of competing publications increases, but magnitude is small
  - Other demand characteristics (e.g. policy) less important
    - Since these factors have been found to influence private R&D, it does not appear that public R&D merely substitutes for other funding sources

Linking Publications and Patents

Linking Publications and Patents

- The ultimate goal of public R&D is to develop new technologies
  - For this, I link publications to patents, using non-patent literature (NPL) references on U.S. energy patents
  - Roach/Cohen (*Management Science* 2013) find non-patent citations are better measures of knowledge flowing from public research than patent citations

- Key question: How long does it take until publications are cited?

Share of articles receiving patent citations

	Biofuels		*Solar*		*Wind*	
	N	% with patent citation	N	% with patent citation	N	% with patent citation
USA						
1991-1995	168.8	4.1%	618.0	4.2%	56.3	8.9%
1996-2000	318.1	7.8%	669.3	6.7%	96.3	4.2%
2001-2005	408.9	4.9%	981.4	4.4%	163.4	6.1%
2006-2011	3532.9	0.7%	4055.2	0.6%	600.6	0.3%
Total	4428.6	1.7%	6323.9	2.2%	916.5	2.3%
foreign						
1991-1995	630.2	0.6%	2054.0	2.8%	264.7	3.0%
1996-2000	959.9	1.2%	3669.7	4.2%	406.8	3.2%
2001-2005	1783.1	1.1%	6172.6	2.3%	758.7	2.2%
2006-2011	12847.1	0.2%	23055.8	0.2%	3268.4	0.2%
Total	16220.4	0.4%	34952.1	1.2%	4698.5	0.9%

Linking Publications and Patents

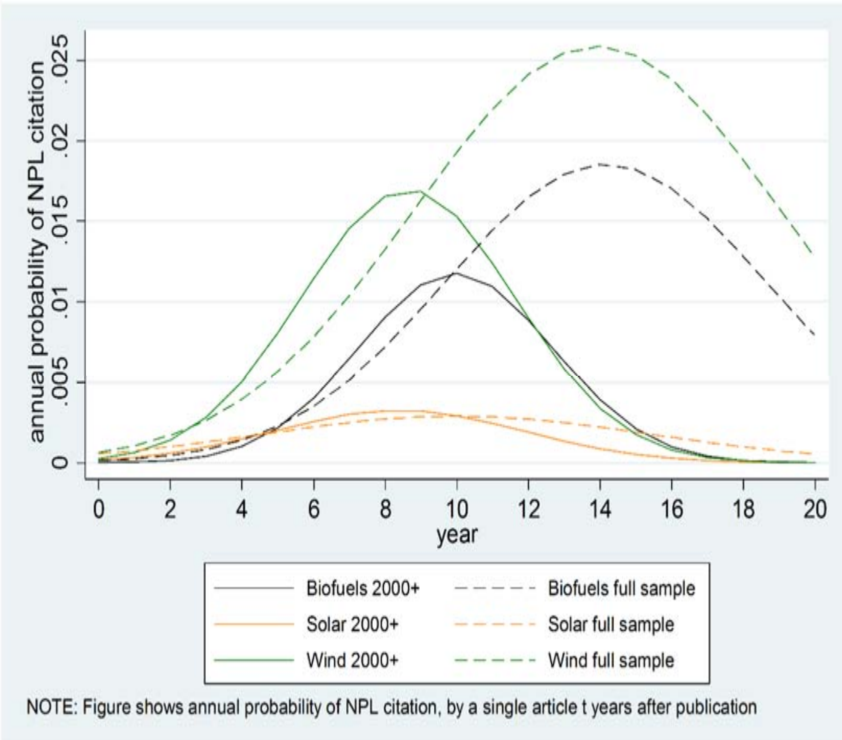
- Because of truncation issues, model time to first NPL citation using a hazard regression
  - Use articles published in 2009 or earlier, with patents granted by 2011
  - Use an exponential baseline hazard, since I explicitly model effect of time using the citation lag
  - Consider both full sample (1991-2009) and articles published since 2000
    - Has time to citation changed as citing opportunities increase?

$$h(t) = \exp(\alpha_0 + \alpha_1 citationlag \ + \ \alpha_2 citationlag^2 \ + \alpha_3 multicountry + \boldsymbol{\gamma}\mathbf{YC_{i,t}})$$

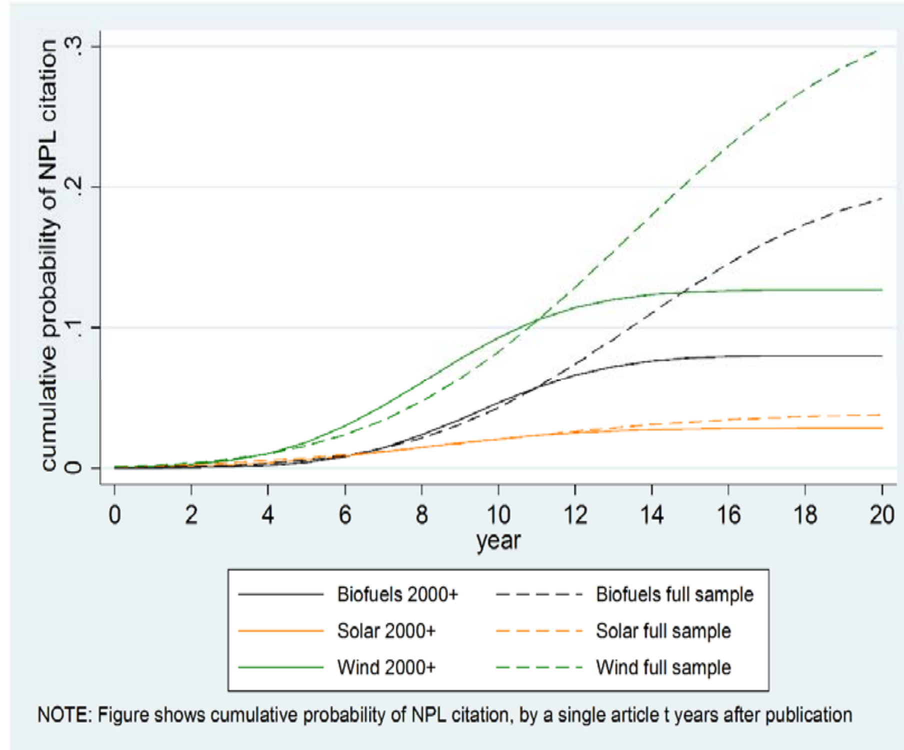
- $\boldsymbol{\gamma}\mathbf{YC_{i,t}}$ represent country by cited year fixed effects
- Controls for different citing opportunities in different countries

Probability of NPL citation over time

Annual probability of NPL citation



Cumulative probability of NPL citation

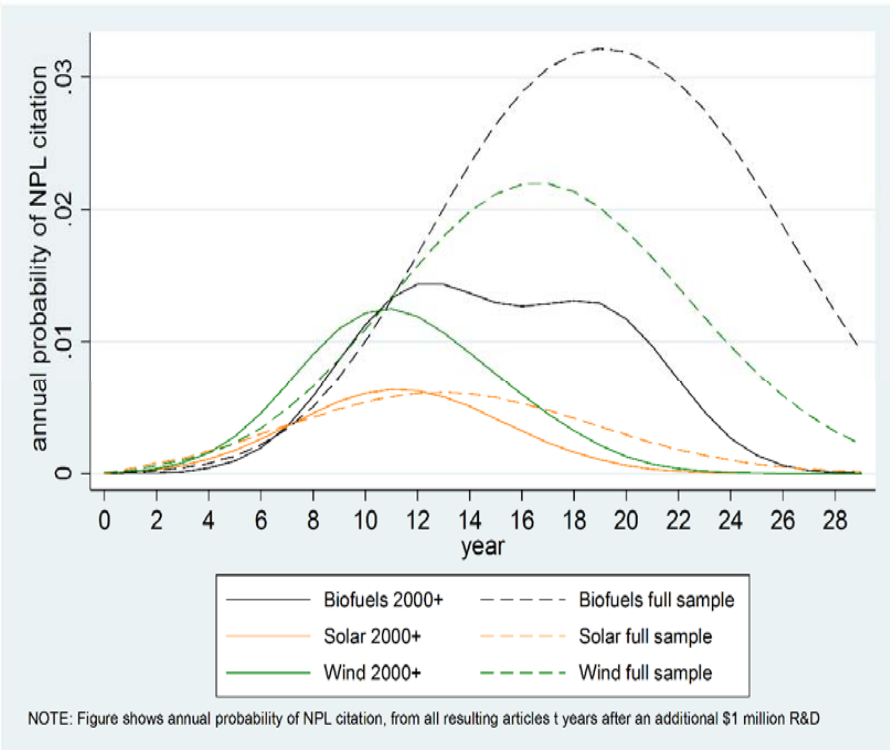


- Peak of annual probability of citation:
  - Full sample: 11-14 years (dashed lines)
  - 2000+ sample: 8-10 years (solid lines)
    - Note: mean patent grant lag is 5 years

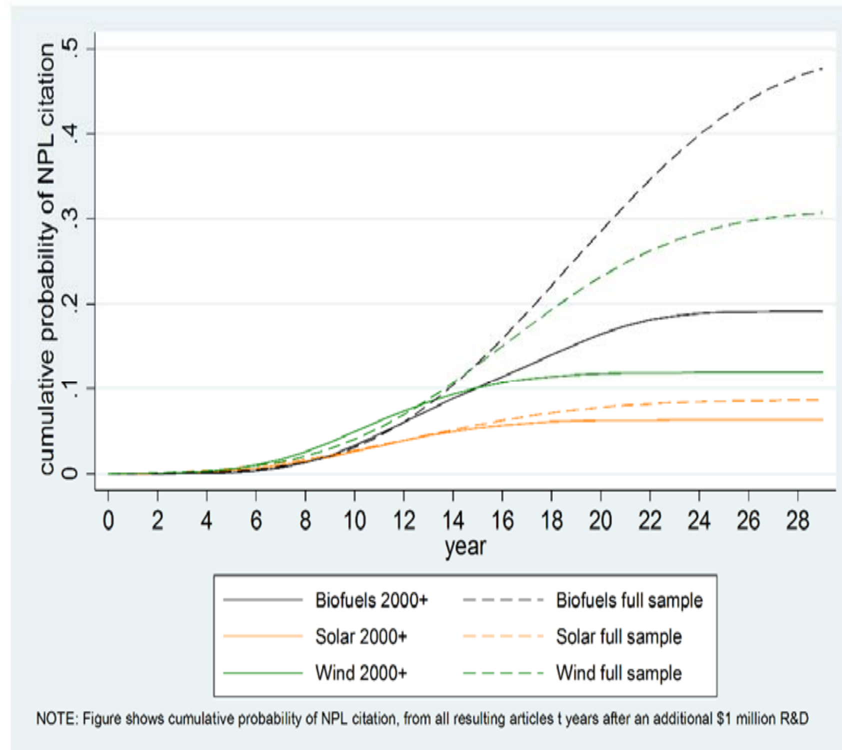
Maxwell | Syracuse University

Increased probability of NPL citation from additional energy R&D

Annual probability of NPL citation



Cumulative probability of NPL citation



- Impact of R&D funding must also consider lags to publication
  - Full sample: 13-19 years (dashed lines)
  - 2000+ sample: 10-12 years (solid lines)
- Suggests substantial lags needed to evaluate energy R&D

Knowledge Flows in Renewable Energy

- Popp (*Research Policy*, 2017) extends this work by providing more detail on the knowledge flows between published and patented clean energy research
  - To help decision makers target R&D funds towards both the technologies and institutions where they will be more successful
  - Two questions:

1. What information is most useful to the development of new technology? Does high quality science lead to commercial success?
   - Do article/article citations also indicate relevance for applied work?
2. Which institutions produce the most valuable research?
   - Do collaborations between public and private research organizations increase flows of knowledge among groups?

Do highly cited articles generate applied technology?

Do highly cited articles generate applied technology?

- Many researchers use citations as a proxy for article quality

- But, are highly cited scientific articles also more likely to be cited by patents?
  - Or, are the articles that inventors of new technology find useful different from those that other academic researchers find useful?

Do highly cited articles generate applied technology?

- Results are non-linear: highly cited articles are more likely to be cited by patents
  - Except for solar, no significant results at 5% level until 75th percentile of article citations
  - Increased probability of citation is much higher in top percentiles of article citations
    - Articles in the 90th-95th percentile for either actual publications or a "quality index" are 206-360 percent more likely to be cited by a patent
    - In the 95th-100th percentile, articles are 278-576% more likely to be cited by a patent

Do highly cited articles generate applied technology?

- Little evidence of the need for "intermediary" publications linking highly cited basic science to applied technologies
  - Look at citations to "children" of highly cited patents: articles that cite other alternative energy articles with citation counts in the top 90th percentile
  - Coefficient on children is positive in all but one case, but only significant for solar energy
    - Magnitude of the effect is smaller: children of highly cited patents are an additional 31% more likely to be cited for solar energy
  - Compare to Gittleman and Kogut (2003), who find that what makes successful science does not necessarily lead to successful technology in biotechnology

Knowledge flows across institutions

Knowledge flows across institutions

- I next use these citation data to examine:
  - the quality of articles and patents across different research organizations
  - the flow of knowledge across these institutions
- Focus on five organization types:
  - (1) universities; (2) governments (e.g. government laboratories); (3) research institutes; (4) private companies; (5) other organizations (including individual inventors)
  - Collaborations between two or more institutions are a separate category
    - To focus on public/private technology transfer, separately identify collaborations with a private company partner
  - Based on organizations *performing* research, not funding research

Knowledge flows across institutions

- Use citation cohort model developed by Adam Jaffe & co-authors (e.g. Caballero and Jaffe 1993, Jaffe and Trajtenberg 1996, 1999) to control for other factors influencing citations to estimate knowledge flows across institutions
  - Create groups of publications based on:
    - year of publication,
    - organization(s) represented on the publication,
    - country of origin
  - Model flows of knowledge, measured by the probability of citation, across pairs of cited/citing categories:

$$p_{CTD,CTG} = \frac{c_{CTD,CTG}}{(n_{CTD})(n_{CTG})}$$

Results: Pooled

- Article-article citations
  - University articles more likely to be cited and to cite other work
    - Consistent with the idea that most basic research comes from universities
  - Collaborations help expose research partners to each other's research
    - Company collaborations 3% more likely to be cited than universities *when including self-citations only*
    - Non-company collaborations 2% more likely than universities to cite other work *when including self-citations only*

Results: Pooled

- Patent-patent citations
  - Government research highly valuable
    - Government patents 13.7% more likely to be cited than university patents
  - Collaborative research enhances the flow of knowledge across institutions
    - Non-company collaboration patents 31% more likely to be cited than university patents (although only 10% significance)
      - Excludes self-citations: not just technology transfer within the group
        - » Similarly, these collaborations aren't more likely to cite other research
      - Rather, these appear to make novel contributions more valuable to future researcher

Results: Pooled

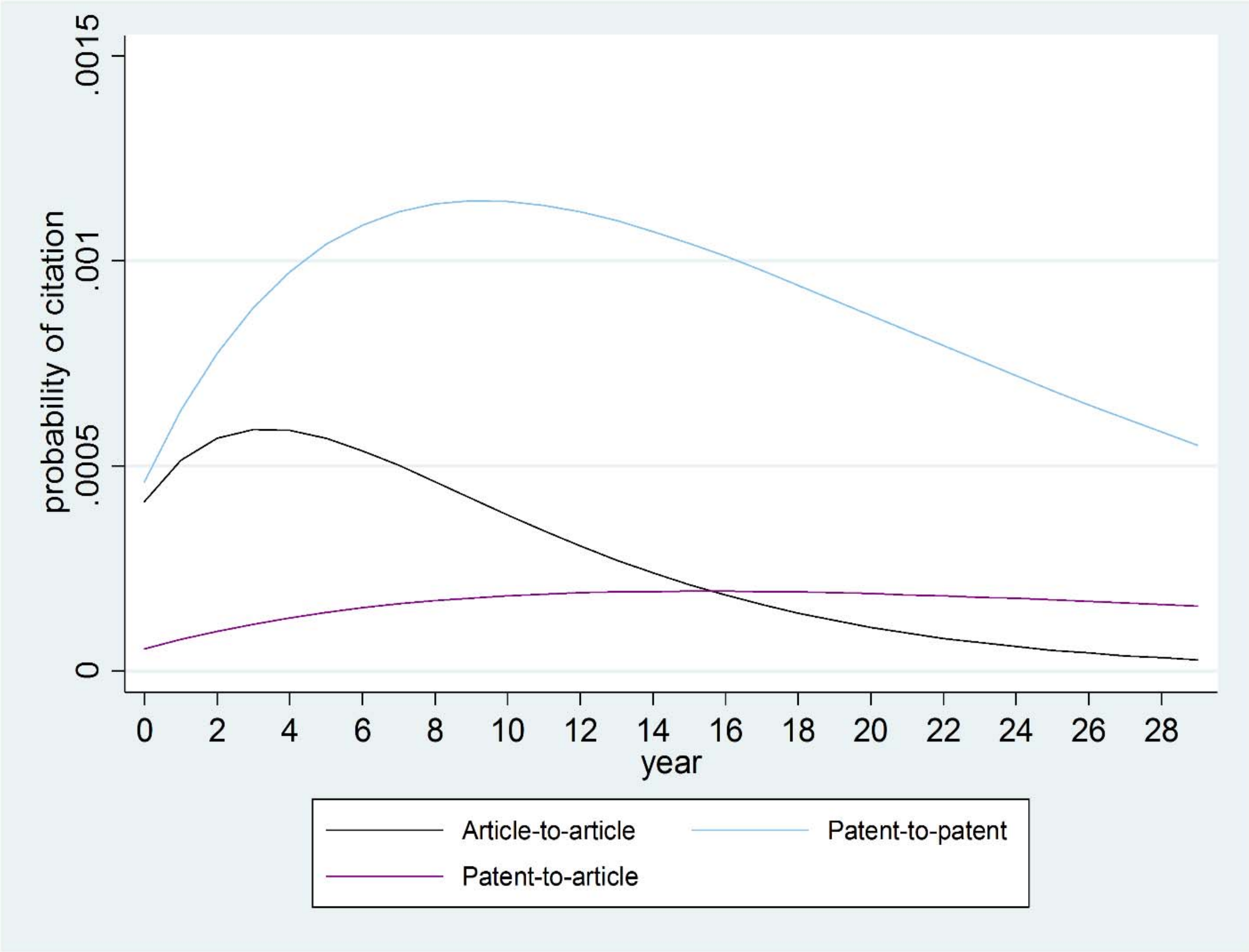
- Patent-article citations
  - Government research remains highly valuable
    - Government articles 14% more likely to be cited by a patent than a university article
  - Universities remain important
    - Cited more frequently than any non-government article
  - Collaborative research exposes research partners to a wider range of knowledge
    - When excluding self-citations, non-company collaborations 60% more likely than university patents to cite other articles

Results: By technology

- Article-article citations
  - University articles generally most cited for biofuels and solar
    - Company collaborations 10% more likely to be cited for solar
  - In contrast, wind appears to be moving towards a more applied stage
    - University research is less important
    - Company (62%) and government (80%) articles most frequently cited for wind
    - Both types of collaborations also highly cited

- Patent-patent citations
  - Government patents highly cited for biofuels and wind, but not solar
  - Private sector patents in biofuels and solar more frequently cited than university patents

Results: Rate of decay and diffusion



Maxwell | Syracuse University

Results: Rate of decay and diffusion

- Knowledge flows between articles and patents peak 15 years after article publication
  - Slightly longer than found in studies of other fields, suggesting that energy research may take longer to progress to a commercialized product
    - Branstatter and Ogura (2005) find that patent citations to scientific publications peak about eight years after article publication
    - Veugelers and Wang (2015) note that the time lag between article publication and patent citation is faster in emerging technologies
    - Finardi (2011) finds lags of just 3-4 years for nanotechnology

Implications for energy R&D policy

- Patience is important
  - Lags between funding and publication are long
- Important to include multiple lags in evaluations of public R&D funding
  - Studies using only a single lagged value of government R&D are likely measuring something else
- Government research can also help new technologies overcome roadblocks to commercialization
  - Research on renewable energy sources produced by government institutions has been particularly helpful moving alternative energy research to an applied stage
    - Government articles not more likely to be cited by other articles, but are more likely to be cited by other patents

Thank You!