ITIF | INFORMATION TECHNOLOGY & INNOVATION FOUNDATION

Side Effects: How Renewable Energy Policies Drive Innovation in Complementary Grid Technologies

KELLY A. STEVENS AND AMIR ROUHOLLAHI | JANUARY 2021

Policies that support renewable energy technologies also drive innovation in complementary technologies for energy storage, grid efficiency, and fast-ramping combustion. Public R&D funding has the most consistent impact and should be increased.

KEY TAKEAWAYS

- Renewable energy technologies provide substantial environmental benefits, but their variability is a major weakness. Complementary technologies are needed to overcome this weakness.
- Previous research has shown that renewable energy policies drive innovation in renewable technologies. This report shows these policies also have the positive side effect of spurring innovation in complementary technologies.
- The effect is assessed using data that measures the impact of seven policies on patents granted from 1992 to 2014 across OECD countries.
- The analysis shows public R&D funding for renewable energy has a consistent, significant, positive impact on innovation in complementary technologies. Environmental taxes and renewable energy certificates also have positive impacts.

INTRODUCTION

Investment in renewable energy sources, such as solar and wind, provide substantial environmental benefits by reducing greenhouse gases and other pollutants from the energy sector. Due to technological innovation and policy interventions, solar and wind power are the fastest growing sources of generation capacity in the United States. However, these resources have a major weakness: variability. Unlike conventional fossil and nuclear plants, they cannot provide firm, dispatchable power. As a result, they provide a much smaller share of electricity generation than their impressive growth rates may suggest: only about 10 percent in the United States in 2020.[1]

Complementary technologies are needed to overcome this weakness. For example, energy storage technologies can store solar energy generated during the day to supply power to homes and factories after the sun has set. Combined cycle combustion plants can ramp up and down quickly to offset fluctuations from renewables. Natural gas and coal plants upgraded with carbon capture can provide firm power at all times. Smart grid technologies can enable grid managers to shift among resources to balance variations from wind and solar generators.

More stringent renewable policies are associated with increased innovation in complementary technologies, as measured by patents.

Previous research has shown that policies targeting environmentally beneficial technologies such as renewable energy can drive innovation in the targeted technologies.[2] However, there has been little research exploring whether such policies have the positive side effect of spurring innovation in complementary technologies. This report aims to fill this gap.

Using data from the Organization for Economic Cooperation and Development (OECD) countries, we find evidence for such an impact. More stringent renewable policies are associated with increased innovation in complementary technologies, as measured by patents. The policies with the greatest impact include public research and development (R&D) spending and renewable energy certificates, such as Renewable Portfolio Standards (RPS) in the United States.

Our findings suggest that policymakers wishing to accelerate innovation in renewable energy, and technologies that complement renewable energy should implement the following recommendations:

- Add or strengthen renewable policies to incentivize innovation in complementary renewable technologies.
- Increase investments in R&D for renewable energy, which have additional benefits to complementary technologies.
- Adopt or strengthen RPS or other market-based demand-pull policies to more broadly stimulate innovation.
- Couple feed-in tariffs (FITs) with other policies, such as R&D, that increase innovation in grid integration technologies.

- Maintain or strengthen environmental taxes for greater innovation in grid-efficiency technologies.

ACCELERATING INNOVATION WITH SUPPLY-PUSH AND DEMAND-PULL POLICIES

In order to reduce carbon emissions and thereby sufficiently address climate change, a diverse set of technologies, including both renewable and complementary technologies, must be developed. A recent report by the International Energy Agency (IEA) shows that many technologies that would be needed to reach net-zero emissions by 2070 have not yet reached the market. They are not yet affordable, reliable, or effective enough to be adopted globally. Innovation is also key to fostering a more resilient and diverse economy, and investment in a renewable energy revolution could spur much needed job growth.[3]

Public policies can correct market failures that hold back innovation. There are two main types of market failure. “Supply-push” policies address the market failure caused by the fact that knowledge is typically a public good. If a firm invests in research, it does not capture all the benefits of this investment. Instead, they spill over to other parts of society and lower the direct returns to the firm. Firms may refrain from making such investments as a result. Public R&D subsidies can incentivize firms to invest in socially optimal levels of research activity.[4]

The other type of market failure is the environmental externality. Firms often pollute the water, air, or land, thereby imposing costs on community health and the environment without having to pay any price themselves. “Demand-pull” policies, such as environmental regulations, can help to address this issue by forcing firms to limit pollution or imposing a price for it.

A noteworthy study by Johnstone et al. explores how both kinds of policies impact innovation for renewable energy technologies. They found a strong link using an empirical cross-country analysis from 1978 to 2003. Consistent with prior work, they found that supply-push policies such as R&D subsides are consistently a significant determinant of renewables innovation. They also found that demand-pull instruments, including market-based environmental regulations, are effective at stimulating innovation.[5]

For instance, broad-based demand-pull policies that set state-wide deployment targets, such as RPS, induce innovation in technologies that are relatively cost competitive with fossil fuel technologies. However, for more costly technologies at earlier stages of development, more targeted policies, such as FITs, are needed to incentivize innovation.

These significant findings lead directly to the question that animates this report. Do supply-push and demand-pull policies that aim at renewable energy technologies also induce innovation in complementary technologies, such as energy storage or combustion technology with fast ramp speeds? To answer this question, we turn to patent data.

MEASURING INNOVATION WITH PATENTS

Patents have long been used as indicators of innovation. A patent provides a temporary monopoly on an invention. This monopoly overcomes the spillover market failure mentioned previously. Without a monopoly, an inventor might lose out to imitators that have not made the same investment in R&D. The fear of losing out might discourage this investment altogether.[6]

The use of patents to measure innovation is not perfect. There are differences in the propensity to patent across technology fields and countries.[7] Simple patent counts require an assumption that all patents carry the same weight and neglect quality, impact, and ease of patentability. However, these issues can be addressed with careful methods.

This study uses data from the European Patent Office's Worldwide Patent Statistical Database (PATSTAT). PATSTAT is a comprehensive source of bibliographic patent data for over 100 patent offices, including the United States Patent Office.[8] We used counts of patents granted per country per year from 1992 through 2014 as our dependent variable.[9] Using patents granted, rather than patents applied for, ensured some level of quality was met for inclusion in our database. We controlled for other factors that affect the time it takes to grant a patent and attrition in our statistical model, which is described in more detail in section 5.

To identify patents in technologies that complement renewable energy, we used the Y02E subclass of the Cooperative Patent Classification codes (CPCs), which includes technologies related to energy generation, transmission, or distribution that reduce greenhouse gas emissions.[10] We examined three relevant complementary technology categories:

- Combustion technologies with mitigation potential (Y02E 20/00), including waste incineration, combined heat and power, combined-cycle power plants, and carbon capture and storage. The fast-ramping nature of some of these combustion technologies, including advanced combined cycle natural gas systems, can assist with renewables integration.[11]
- Grid-efficiency technologies (Y02E 40/00), including flexible AC transmission systems, reactive power compensation, superconducting grid components, and smart grid technologies. Some of these technologies enable grid managers to shift quickly among generators to balance variations in wind and solar output.
- Storage and other enabling technologies (Y02E 60/00), including energy storage in batteries and capacitors, thermal energy storage, mechanical energy storage, hydrogen technologies, and high voltage DC/AC inverters. These technologies assist with grid stability by matching energy demand and supply with fluctuating renewable resources for electricity generation. Generally, hydrogen systems can store energy over longer time scales for community-level systems, while batteries and capacitors enable shorter-duration storage at a smaller scale (10 kW to 100 MW).[12]

We also collected patents related to renewable energy generation (Y02E 10/00) as a robustness check on our models. We found a high correlation between all complementary technology areas and renewables patents (appendix A). The strongest relationship is with storage technologies, indicating these are highly related. Combustion technologies and grid-efficiency technologies are also strongly correlated with renewable technologies, but to a slightly lesser degree. These findings confirm that patent trends in the complementary technology fields identified in this study are similar to renewable energy patenting rates. For this reason, we hypothesize that we will be able to identify spillover effects from renewable policies on complementary technologies.

Figure 1: Patents granted for complementary technologies across four top patenting countries per year

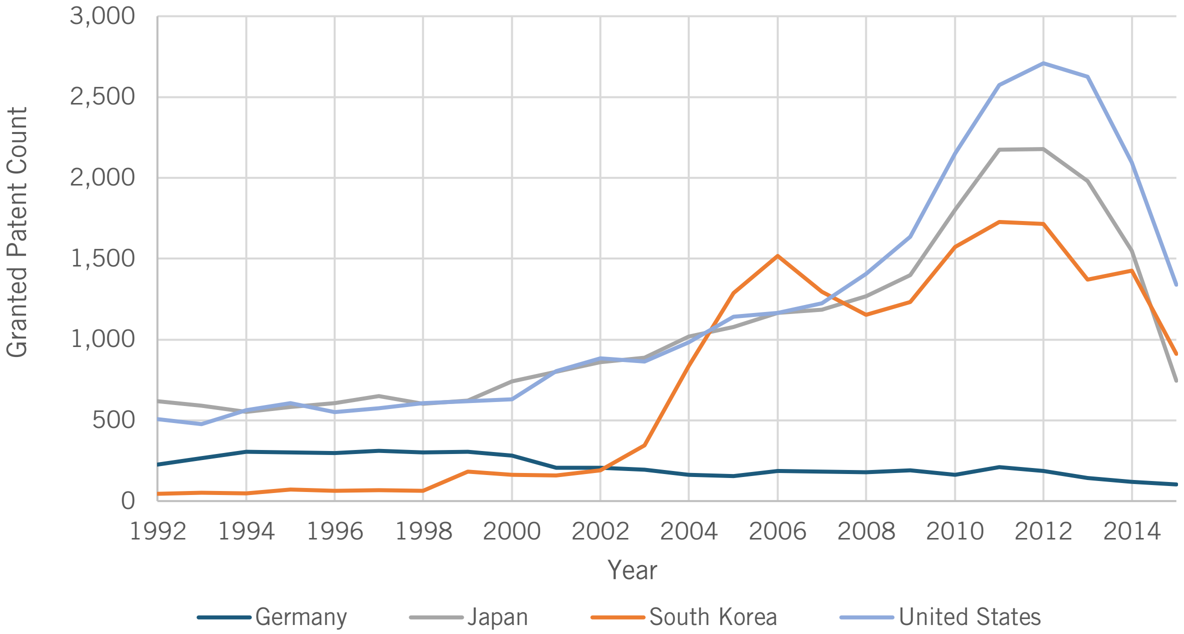


Figure 1 shows the sum of patents granted for all three categories of complementary technologies from 1992 to 2015 for four of the top patenting countries: the United States, Japan, South Korea, and Germany.[13] It shows an uptick in innovation in South Korea beginning in 2003, which was followed by a rapid increase in innovation in these fields in the United States and Japan, and continued growth in South Korea beginning in 2007, which accelerated in 2009. In the United States, one possible source of this innovation uptick was stimulus funding associated with the financial recovery package. There was some attrition in the time series beginning around 2011 that is likely associated with the time lag to grant a patent after application. However, we controlled for this potentially confounding effect in the model.

Figure 2: Normalized patent counts for the United States for the three complementary renewable technology areas and renewable technologies

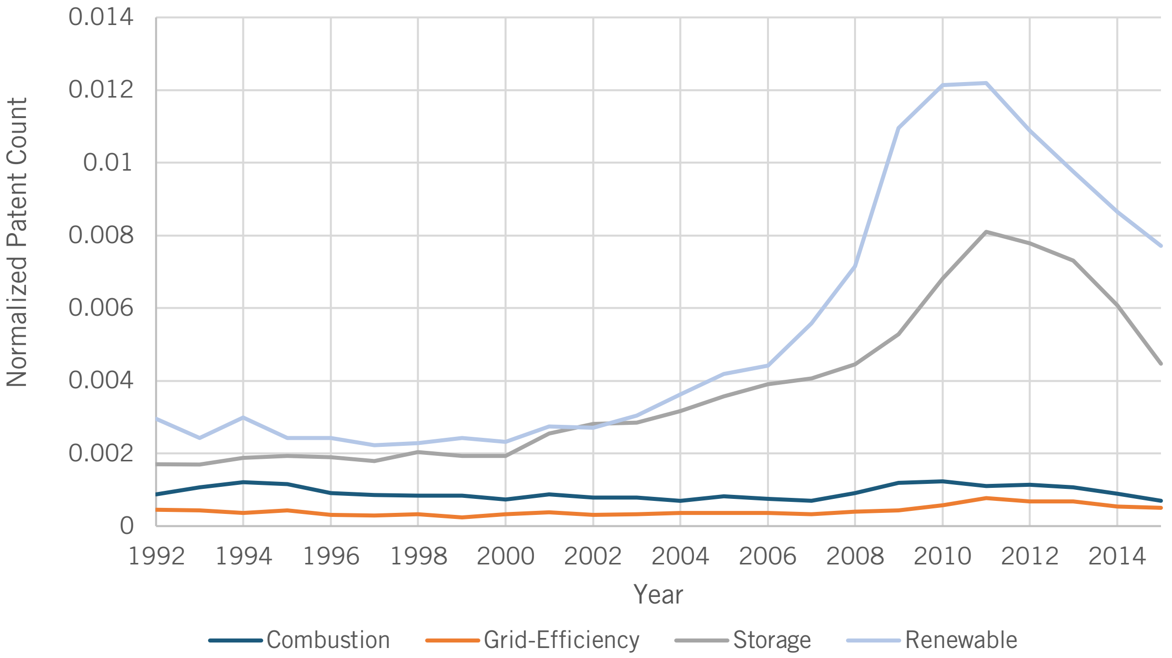


Figure 2 shows patent counts for the United States for each of the three complementary technology groups as well as renewable technologies themselves, normalized by dividing each by the total number of patents granted in the United States in the relevant year. Renewable and storage technologies follow a similar pattern: Each had steady gains in the early 2000s, followed by rapid increases in patenting from 2006 to 2010, and then they began to decline. Similar trends have been identified by IEA and Information Technology and Information Foundation (ITIF).[14] Combustion and grid efficiency technologies account for smaller shares of total patents granted, but patenting activity has remained fairly constant over time.

At a time when we face increased need for innovation in clean energy, patenting activity has been on a downward trend after peaking in 2011–2012. This trend is a concerning harbinger of the state of technological change and national commitments to clean energy innovation across the globe.

MEASURING RENEWABLES POLICIES

We seek to understand whether the variations in innovation as measured by the previously listed patent counts are caused by policies that encourage renewables. To measure these policies, we used data drawn from the Environmental Policy Stringency (EPS) dataset gathered by OECD.[15] OECD developed this measurement tool in order to assess the ambition of national and subnational policies. The EPS index compares the stringency of environmental policies across countries and time for different types of policies, whether market-based or non-market-based. The index is based primarily on quantitative data, such as tax rates, and typically normalized by relevant information such as electricity prices to address inherent variations across countries and time.[16]

We used seven of OECD’s policy measures in our study to evaluate the impact of renewable policies on technology innovation.

- **FITs for solar power** guarantee a set price, usually above retail, to electricity generators such as rooftop solar panel owners. They are commonly used in Europe as well as in the United States.
- **FITs for wind power** operate the same way as those for solar power do.
- **Tradeable certificates for carbon dioxide emissions** allow emitters to buy and sell the right to emit under a cap-and-trade system. The Regional Greenhouse Gas Initiative in 11 northeastern states in the United States, for example, issues such certificates.
- **Renewable energy certificates** require utilities to produce or purchase a certain share of renewable power as part of their portfolio. RPS policies in some U.S. states issue such certificates.
- **Energy efficiency certificates** establish energy savings obligations for utilities. Certificates are awarded when utilities implement energy efficiency measures, which can be traded among utilities in a market. They are used in some European countries.
- **Environmental taxes** apply an additional cost based on emissions of certain pollutants to encourage citizens and investors to choose low-emission energy sources. In the United States, the Acid Rain Program and the 2006 NOx Budget Trading Program apply such taxes. We used the measure for all environmental taxes as a whole in this study.[17]
- **Government R&D expenditures** are used to incentivize innovation and commercialization of clean energy technology. In the United States, R&D has been disbursed through clean energy programs such as the Department of Energy’s Advanced Research Projects Agency – Energy (ARPA-E) to fund high-potential projects.

For each of the seven renewables policies, OECD has developed a score on a scale of 0 to 6 across countries and over time. Our dataset therefore reflects the relative ambition of each country’s position on each instrument. The descriptive statistics and specific measurements used in the EPS are provided in table 1.

Table 1: Measurements of renewables policies[18]

Policy	Measurement	Mean	St. Dev.	Min	Max
Feed-in-Tariff Solar	Price/kWh	1.53	2.09	0	6
Feed-in-Tariff Wind	Price/kWh	1.68	2.15	0	6
Government R&D for Renewable Energy	% of GDP	2.21	1.31	0	6
Environmental Taxes	Price/ton emissions	1.59	0.64	0.5	4
Certificates: CO_2	Price per CO_2 allowance	1.16	2.01	0	6
Certificates: Energy Efficiency	% electricity savings to be delivered annually	0.21	0.81	0	6
Certificates: Renewable Energy	% renewable electricity that to be procured annually	0.61	1.42	0	6
Overall Mean	Mean of the policy scores over the entire time period	1.51	0.40	0.79	2.49

Figure 3: Mean renewables policy scores by country, 1992–2015

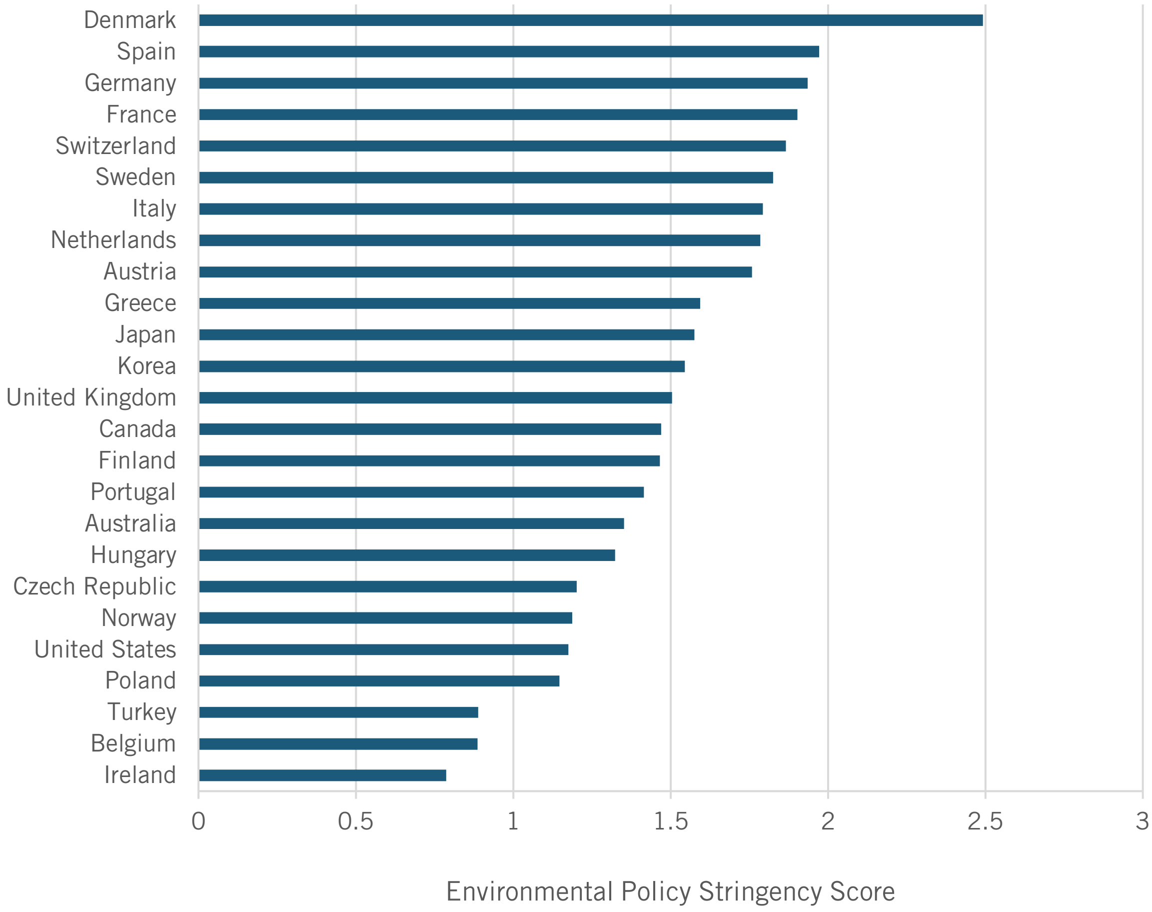
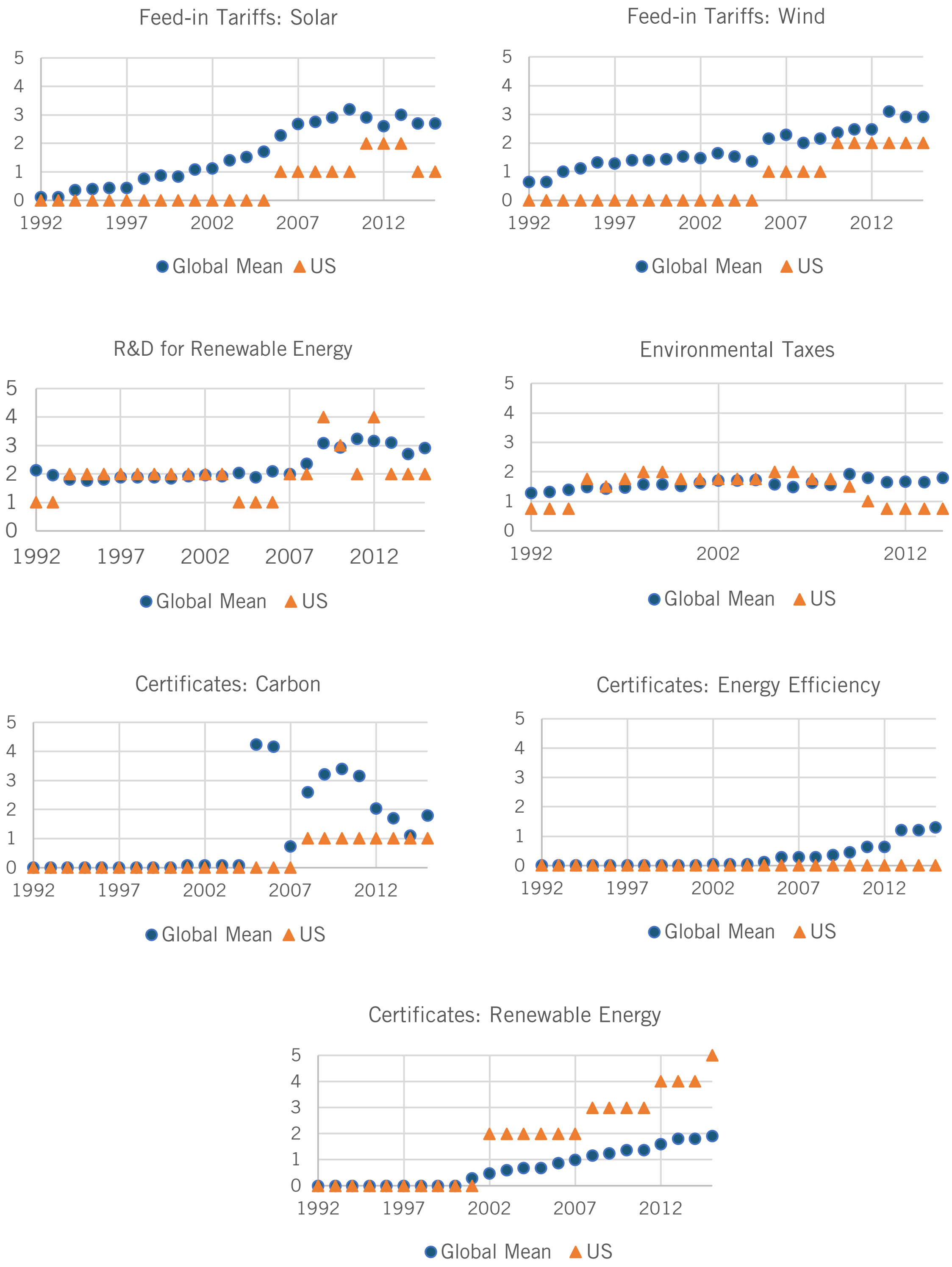


Figure 4: Renewable policy scores for the United States relative to the global mean, 1992–2015



Feed-in Tariffs: Solar

Feed-in Tariffs: Wind

R&D for Renewable Energy

Environmental Taxes

Certificates: Carbon

Certificates: Energy Efficiency

Certificates: Renewable Energy

Figure 3 shows the mean scores for the seven policies for each country between 1992 and 2015. The mean score provides a sense of overall policy stringency. While the index ranges from 0 to 6, the mean scores in figure 3 are low because few countries had ambitious renewables policies in the 1990s. Overall, larger European countries such as Spain and Germany earned the highest scores. The United Kingdom, South Korea, and Japan were about average, while smaller European countries and the United States occupy the lower end of the scale. (Appendix A shows the correlations across policies, which show the solar and wind FITs are highly correlated, but most others are not. This finding means multicollinearity should not be an issue in the statistical analysis.)

Figure 4 compares the United States' score on each of the seven policies included in this study with OECD means. The top set of graphs in figure 4 shows FITs for solar and wind, which were not used in the United States, even at the subnational level, until 2006. Mean scores for these policies have been steadily increasing across the rest of the OECD, so the United States has had low scores throughout the time series.

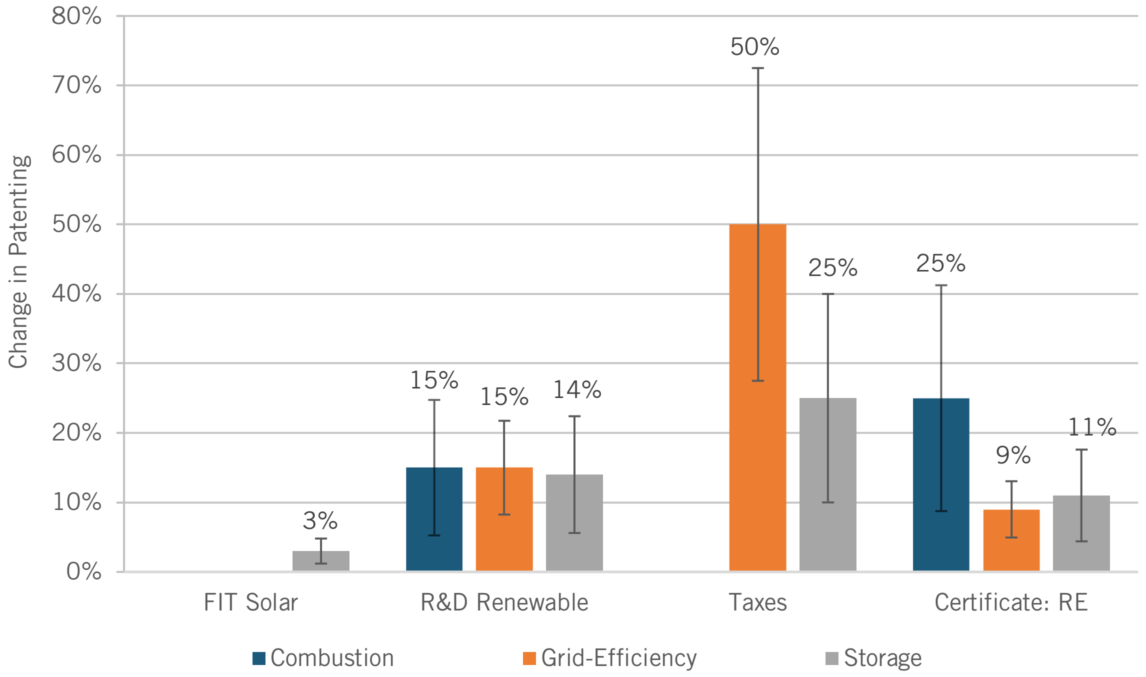
The second row of graphs illustrates the scores for R&D subsidies for renewable energy and environmental taxes. OECD mean scores for R&D subsidies for the former were steady until 2009 when spending increased. The U.S. score follows a similar trend, also increasing in 2009 and 2012. The 2009 spike is likely associated with the 2009 American Recovery and Reinvestment Act (ARRA). Since these scores are relative across countries and time, the discontinuity in the U.S. R&D score after 2009 could have been caused by increased spending in other countries during this time. While the United States is one of the largest funders of renewable energy R&D in absolute terms, it does not do as well when this funding is measured as a share of gross domestic product (GDP), as it is here. [19] Environmental taxes have been consistently low in the United States, dropping away from the OECD mean after 2009.

The third row of graphs shows the scores for carbon (left) and energy efficiency (right) tradable certificates. Carbon certificate scores jumped across OECD in 2009, while only increasing slightly in the United States in 2008 due to the Regional Greenhouse Gas Initiative in the Northeast. In 2013, California started a cap-and-trade program for carbon emissions, which is accounted for in these scores. The United States does not use energy efficiency tradable certificates, which are not common in other OECD countries either. The bottom graph represents renewable energy certificates, an area in which the United States consistently has scored higher than other nations since 2001. RPS have so far been adopted by 30 U.S. states and the District of Columbia.[20]

FINDINGS: AMBITIOUS RENEWABLES POLICIES DRIVE INNOVATION IN COMPLEMENTARY TECHNOLOGIES

Our statistical model, which is described in greater detail in appendix B, links together our measures of policy and innovation. We've included several controls as well that might otherwise bias our findings because they tend to be correlated with innovation, including energy consumption and electricity prices.[21] In addition, we've included dummy variables to correct for invariant country and time characteristics.

Figure 5: Percentage change in patenting as a result of renewables policies



Our results show that some renewable policies stimulate innovation in complementary technologies. The magnitude of the impact varies by policy, and some policies have differential impacts across technology categories. Each technology field is impacted in a statistically significant way by at least one policy. Figure 5 shows the percentage increase in patents granted in each of the three complementary technology categories caused by a one-unit change in each of the policies measured for which we found a statistically significant relationship. The error bars represent the approximate 95 percent confidence interval for each result.

The FIT for solar has a weakly positive statistically significant impact on storage technology patenting—but it does not have a statistically significant relationship with the other two technology fields. The FIT for wind does not have a statistically significant impact on any of the complementary technology fields. Further analysis using one FIT variable for both wind and solar has no statistically significant relationships with any complementary technology field. Therefore, we concluded that the FITs have very limited, if any, impact incentivizing innovation in complementary technologies.

Public R&D funding for renewable energy, however, has a consistently significant impact. A one-unit increase in the score on this component corresponds to about a 15 percent increase in patenting across all three categories of complementary technologies.

Environmental taxes drive innovation in grid-efficiency and storage technologies, but not in combustion technologies. A one-unit increase in the environmental tax score corresponds to a 50 percent increase in grid-efficiency patents and a 25 percent increase in storage technologies.

Renewable energy certificates have the largest impact on combustion technology. A one-unit increase in the score on this variable leads to a 25 percent increase in combustion patenting activity. Renewable energy certificates also incentivize increased patenting in grid-efficiency and energy storage technologies, but to a smaller extent.

Tradeable certificates for carbon dioxide emissions, on the other hand, have a small (less than 10 percent) negative impact on patenting for most technology categories, and are therefore not included on the graph but can be seen in appendix C. Energy efficiency certificates have no statistically significant impact.[22] Perhaps such programs have not been around long enough, and prices have been too low, to have a measurable impact.

POLICY IMPLICATIONS

Our findings have several implications for policies that would increase innovation and enhance renewables integration to better support deep decarbonization. These proposals take on heightened significance in light of the fact that patenting activity in key fields has declined in recent years (figure 2), even though the need for innovation has only grown stronger.

Add or strengthen renewable policies to incentivize innovation in complementary renewable technologies.

Countries with stronger policies to encourage renewables adoption also stimulate patenting in complementary technologies. These technologies include fast-ramping and carbon capture technologies, long- and short-duration storage systems, and technologies for efficient electrical power generation, transmission, and distribution. In other words, renewable policies have positive unintended consequences for enabling technologies that alleviate some of renewable technologies' challenges with grid variability and integration. Countries that have relatively lower renewables policy scores, such as the United States, could enhance or add these policies at the national and subnational level to stimulate this type of innovation (figure 3).

Increase investments in R&D for renewable energy, which have additional benefits to complementary technologies.

Our results also show that public R&D funding for renewable energy has a statistically significant and positive impact on patenting across all three fields of complementary technology. For the United States, a one-unit increase in this score would mean an increase in R&D for renewable energy of about 11 percent from current levels of investment, which would in turn add about 15 percent to U.S. patent totals. In the wake of COVID-19 and the toll the pandemic has taken on the economy, governments should resist the temptation to cut R&D funding and instead increase their investments in renewables R&D. [23]

Adopt or strengthen RPS or other market-based demand-pull policies to more broadly stimulate innovation.

Renewable energy certificates, such as RPS, are also effective at stimulating innovation in technologies that complement renewable energy. If the United States adopted a national clean energy standard that required at least 15 percent of all electricity to be generated from renewable resources, it would increase patenting in technologies that complement renewables by an additional 10 to 25 percent.

Couple FITs with other policies, such as R&D, that increase innovation in grid integration technologies.

Some market-oriented policies, such as the FITs for solar and wind, do not have a significant impact on patenting of complementary technologies, and may even lead to reductions. It is likely that the targeted nature of these policies limits their spillover effects. These policies should be coupled with other policies, such as renewable energy certificates and R&D funding, that increase innovation in complementary fields.

Strengthen or maintain environmental taxes for greater innovation in grid-efficiency technologies.

Our results show environmental taxes increase patenting in complementary technologies, but carbon taxes have generally been too low among OECD countries to have a powerful effect. Raising such taxes into the range recommended by the World Bank ($40–80/tCO$_2$) would likely stimulate such patenting.[24]

CONCLUSION

This report evaluates the impact of renewables policies in OECD countries on patenting rates of technologies that complement renewable energy. These complementary technologies assist with the integration of renewable resources, particularly intermittent sources such as solar and wind, and assure more grid stability and power quality. We find that countries with strong renewable policies have greater rates of complementary technology patenting, indicating there are spillover effects from renewables policies. Public R&D spending for renewable energy, renewable energy certificates, and environmental taxes are the three most effective policies for incentivizing innovation.

Innovation remains an important piece of all carbon-reduction strategies around the globe, but it will not occur at a sufficient rate without policy incentives. Renewable policies stimulate innovation more broadly than was previously understood. They have the potential to strengthen renewables integration, improve power quality, and enhance resiliency across systems with high levels of electricity generated from renewable resources.

APPENDIX A: CORRELATION TABLES

Table A1: Correlations from granted patent counts in the three complementary renewable area and with renewable patents

	Combustion	Efficiency	Storage	Renewable
Combustion	1			
Efficiency	0.9193	1		
Storage	0.8644	0.8846	1	
Renewable	0.8405	0.8474	0.9482	1

Table A2: Correlations across renewable energy policies measured through OECD EPS

	FIT Solar	FIT Wind	R&D for RE	Taxes	Cert. CO_2	Cert. Energy Efficiency	Cert. Renewable Energy
FIT Solar	1						
FIT Wind	0.647	1					
R&D for RE	0.085	0.081	1				
Taxes	0.059	-0.020	0.184	1			
Cert. CO_2	0.242	0.045	0.236	0.030	1		
Cert. Energy Efficiency	0.224	0.079	0.092	0.174	0.223	1	
Cert. Renewable Energy	0.006	-0.113	0.112	0.070	0.316	0.275	1

APPENDIX B: METHOD

For this study we used a negative binomial to model the relationship between renewable policies and complementary renewable technology innovation (equation 1). A negative binomial model uses a Poisson process, commonly used with over-dispersed count data, which is common in patent count data. The Poisson process allows transformation of the predicted outcome, letting nonlinear relationships be linearized between the dependent variables and the predictors. The standard errors are robust to control for heteroscedasticity.

$$Patents_{i,t} = \beta_1(Policy_{i,t}) + \beta_2(Consumption_{i,t}) + \beta_3(Price_{i,t}) + \alpha_i + \sigma_t + \varepsilon_{i,t} \text{ (eq. 1)}$$

In addition to the EPS data as the main independent variable of interest, we included several controls that may also contribute to complementary technology innovation. Countries with higher growing energy consumption or high electricity prices may have increased incentive to innovate and lower their costs (Johnstone et al., 2010). Therefore, we controlled for energy consumption using data provided from IEA‘s World Energy Balances.[25] Electricity prices were from IEA’s Energy Prices and Taxes report.[26] Additionally, countries with a higher capacity and propensity to innovate may also be more likely to patent innovations, therefore there are country dummies to control for all time invariant country characteristics (α_i). Last, since we used granted patents that taper off in volume due to attrition and the time it takes to grant patents toward the later part of the time series, we used a year dummy to control for all time invariant year effects, such as attrition (σ_t).

APPENDIX C: FULL MODEL RESULTS

Table C1: Increase or decrease in patenting due to the policy based on the full regression results. Bolded results are above 95% statistical significance

	Complementary Tech.			
Policy	Combustion	Efficiency	Storage	Renewable
FIT Solar	6%	2%	**4%**	**4%**
FIT Wind	-4%	-4%	-1%	**-6%**
R&D Renewable	**16%**	**15%**	**14%**	**6%**
Taxes	11%	**50%**	**25%**	**25%**
Certificate: CO_2	**-7%**	**-4%**	**-9%**	**-6%**
Certificate: EE	-8%	2%	6%	4%
Certificate: RE	**25%**	**10%**	**11%**	**10%**

Acknowledgments

The authors would like to acknowledge support from the University of Central Florida for conducting this study. Detailed feedback was provided by Colin Cunliff and David Hart at ITIF. The Alfred P. Sloan Foundation provided support to ITIF for an energy innovation “boot camp” for early-career scholars, in which Kelly Stevens participated, and which led to this report.

About the Authors

Kelly Stevens is an assistant professor at the School of Public Administration and Resilient, Intelligent, and Sustainable Energy Systems (RISES) research cluster member at the University of Central Florida. Dr. Stevens conducts interdisciplinary research on energy and environmental policy, science and technology policy, and innovation. Her work focuses on the U.S. electricity sector, climate change policies, air pollution, and community resilience, with funding from the National Science Foundation, Alliance for Market Solutions, and National Hazards Center, among others.

Amir Rouhollahi received a PhD from the University of Central Florida’s Department of Mechanical and Aerospace Engineering. Dr. Rouhollahi has extensive experience in mathematical modeling, data analysis, and machine learning applications in various biomedical and industrial projects.

About ITIF

The Information Technology and Innovation Foundation (ITIF) is a nonprofit, nonpartisan research and educational institute focusing on the intersection of technological innovation and public policy. Recognized as the world’s leading science and technology think tank, ITIF’s mission is to formulate and promote policy solutions that accelerate innovation and boost productivity to spur growth, opportunity, and progress.

For more information, visit us at www.itif.org.

ENDNOTES

1. According to IEA's Monthly Energy Review for August 2020, based on electric power sector generation from June 2019–May 2020.
2. Adam B. Jaffe, Richard G. Newell, and Robert N. Stavins, "Technological change and the environment," *Environmental and Resources Economics* 22 (2002): 41–69, https://doi.org/10.1023/A:1015519401088; David Popp, "Lessons from patents: Using patents to measure technological change in environmental models," *Ecological Economics* 54 (2005): 209–226, https://doi.org/10.1016/j.ecolecon.2005.01.001; Nick Johnstone, Ivan Haščič, and David Popp, "Renewable Energy Policies and Technologic Innovation: Evidence Based on Patent Counts," *Environmental Resource Economics* 45 (2010): 133–155, https://doi.org/10.1007/s10640-009-9309-1.
3. David Hart and William Bonvillian, "Policymakers must beware of technology lock-in for energy storage," *The Hill*, April 30, 2018, https://thehill.com/opinion/technology/385503-policymakers-must-beware-of-technology-lock-in-for-energy-storage; International Energy Administration (IEA*), Energy Technology Perspectives 2020: A Special Report on Clean Energy Innovation* (Paris: IEA, 2020), https://webstore.iea.org/energy-technology-perspectives-2020-special-report-on-clean-energy-innovation.
4. David Popp, "Innovation and Climate Change," Annual Review of Resource Economics 2 (2010): 275–282, https://doi.org/10.1146/annurev.resource.012809.103929.
5. Johnstone, Haščič, and Popp, "Renewable Energy Policies and Technologic Innovation: Evidence Based on Patent Counts."; Popp, "Lessons from patents: Using patents to measure technological change in environmental models;" Alkis Pitelis, Nicholas Vasilakos, and Konstantinos Chalvatzis, "Fostering innovation in renewable energy technologies: choice of policy instruments and effectiveness," *Renewable Energy* 151 (2020): 1163–1172, https://doi.org/10.1016/j.renene.2019.11.100.
6. Zvi Griliches, "Patent statistics as economic indicators: a survey," Journal of Economic Literature 28, no. 4 (1990): 1661–1707.
7. Popp, "Lessons from patents: Using patents to measure technological change in environmental models."
8. Elisa Lanzi, Elena Verdolini, and Ivan Haščič, "Efficiency-improving fossil fuel technologies for electricity generation: Data selection and trends," Energy Policy 39, no. 11 (November 2011): 7000–7014, https://10.1016/j.enpol.2011.07.052; Gaétan de Rassenfosse, et al., "The worldwide count of priority patents: A new indicator of inventive activity," *Research Policy* 42, no. 3 (2013): 720–737, https://dx.doi.org/10.1016/j.respol.2012.11.002.
9. We used granted patents because the USPTO did not provide data on patent applications that were not granted before 2000.
10. More on the Y02E subclass can be found from the USPTO at https://www.uspto.gov/web/patents/classification/cpc/html/cpc-Y02E.html#Y02E.

11. Elena Verdolini, Francesco Vona, and David Popp, "Bridging the gap: Do fast-reacting fossil technologies facilitate renewable energy diffusion?" *Energy Policy* 116 (May 2018): 242–256, https://doi.org/10.1016/j.enpol.2018.01.058.

12. Erik Wolf, "Large-Scale Hydrogen Energy Storage," in *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*, edited by Patrick T. Moseley and Jürgen Garche (Amsterdam: Elsevier, 2015), 129–142.

13. This is a raw count of patents rather than a normalized count, therefore some of the high patenting activity in certain countries, such as the United States, can be attributed to higher overall rates of patenting. This does not necessarily indicate they are leaders in renewable energy innovation.

14. IEA, *Energy Technology Perspectives 2020: A Special Report on Clean Energy Innovation*; Colin Cunliff, "Omission Innovation: The Missing Element in Most Countries' Response to Climate Change" (ITIF, December 2018), https://itif.org/publications/2018/12/10/omission-innovation-missing-element-most-countries-response-climate-change.

15. The OECD environmental policy stringency score for OECD countries is available at https://stats.oecd.org/Index.aspx?DataSetCode=EPS.

16. Enrico Botta and Tomasz Koźluk, "Measuring Environmental Policy Stringency in OECD Countries: A Composite Index Approach" (working paper, OECD Economics Department, 2014), https://dx.doi.org/10.1787/5jxrjnc45gvg-en.

17. Since the OECD EPS index does not include a policy for emissions trading programs for criteria pollutants, such as NOx and SOx, they are converted to a price/ton emissions tax value using permit prices. We used environmental taxes rather than carbon taxes because the EPS score for carbon taxes in mostly very low, as most countries do not have high carbon taxes instituted, or if they do, they are a recent occurrence.

18. Botta and Koźluk, "Measuring Environmental Policy Stringency in OECD Countries: A Composite Index Approach."

19. International Energy Agency, "2018 and 2019 budgets by technology in selected IEA countries and the European Union," (Paris: IEA, 2020), https://www.iea.org/data-and-statistics/charts/2018-and-2019-budgets-by-technology-in-selected-iea-countries-and-the-european-union.

20. California Air Resources Board, "AB32 Global Warming Solutions Act of 2006," news release, September 28, 2018, https://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006; NC Clean Energy Center, DSIRE database, (detailed summary maps; accessed October 20, 2020), https://www.dsireusa.org/resources/detailed-summary-maps/.

21. International Energy Administration (IEA), World Energy Balances, (final consumption by sector and source, residential; accessed February 10, 2020), https://www.iea.org/reports/world-energy-balances-overview; International Energy Administration, Energy Prices and Taxes, (electricity prices for households in USD/MWh

(using PPPs), accessed February 10, 2020), https://www.iea.org/subscribe-to-data-services/prices-and-taxes.

22. These results are not shown in figure 5 since only positive relationships above 90 percent statistical significance are displayed in the figure. Appendix C has the full model results.
23. IEA, *Energy Technology Perspectives 2020: A Special Report on Clean Energy Innovation.*
24. World Bank Group, State and Trends of Carbon Pricing 2019 (Washington, D.C.: World Bank, 2019), https://openknowledge.worldbank.org/handle/10986/31755.
25. IEA, World Energy Balances.
26. IEA, Energy Prices and Taxes.