Inducing and Accelerating Clean Energy Innovation with ‘Mission Innovation’ and Evidence-Based Policy Design

By Jacquelyn Pless,[a,*] Cameron Hepburn,[b] John Rhys,[c] and Niall Farrell[d]

Abstract

Clean energy innovation is pivotal for meeting future energy needs and eliminating harmful emissions, but it will require substantial public research and development (R&D) funding. Equally important is spending such resources *wisely*. We address these two components of energy innovation policy by examining: 1) the optimal level of government-funded R&D support for clean energy innovation, and 2) barriers to providing evidence on innovation policy effectiveness. Our estimates suggest that current public investment in clean energy R&D should increase substantially, by perhaps fivefold, at a pace that ensures money is well spent. We discuss the barriers to studying innovation policy effectiveness and provide policy recommendations for generating a wider body of evidence on which innovation policies work and why, including increased use of innovation randomized control trials.

JEL-Classification: O3, Q01, Q48, Q55, Q58

Keywords: Innovation, research and development (R&D), clean energy, technological progress

[a]University of Oxford, Institute for New Economic Thinking at the Oxford Martin School; Eagle House, Oxford OX2 6ED UK, email: jacquelyn.pless@inet.ox.ac.uk

[b]University of Oxford, Smith School of Enterprise and the Environment and the Institute for New Economic Thinking at the Oxford Martin School, University of Oxford, UK; London School of Economics and Political Science, Grantham Research Institute UK

[c]University of Oxford, Oxford Martin Programme on Integrating Renewable Energy

[d]University of Oxford, Institute for New Economic Thinking at the Oxford Martin School

* Corresponding author

Acknowledgements: We are grateful to David Popp for his comments on this paper, and to Ryan Bayliss and Stephen Heidari-Robinson for insightful discussions regarding scientific innovation and policy. We also gratefully acknowledge the Oxford Martin Programme on Integrating Renewable Energy at the Oxford Martin School, University of Oxford, for financial support.

I. Introduction

Innovation is vital for transitioning to a clean energy system at lowest cost. The Paris agreement climate targets will likely be impossible to achieve without innovation that develops cheaper forms of net-zero carbon energy. Clean, cost-competitive technologies must be deployed rapidly at scale, in preference of fossil technologies, to reduce the risk of stranded assets (Pfeiffer, 2016). Yet while the costs of existing renewable electricity generating technologies are falling (Farmer and Lafond, 2016), and scientific research is unlocking new opportunities, deployment is not ramping up fast enough to achieve deep decarbonisation of energy systems in the time required (IEA, 2015). The global economy is unlikely to stop relying on fossil fuels in time to stabilise temperatures at safe levels in the absence of substantial policy intervention (Covert et al., 2016), and delaying intervention could be costly (Acemoglu et al., 2012; Acemoglu et al., 2016).

Avoiding these costs would require a substantial acceleration of effort, including in public research and development (R&D) funding. There are two key market failures that policy should address. First, simple economics shows that greenhouse gas emissions should be priced to account for environmental externalities, whether by carbon taxes, cap-and-trade, emission reduction credits, and/or fossil fuel subsidy reductions. Second, there are large spillovers associated with knowledge creation (Nelson, 1959; Arrow, 1962), and other barriers to innovation, implying that underinvestment in basic R&D results without government intervention (Jaffe et al., 2005). This second market failure is the focus of this Perspective. Emissions pricing in itself provides incentives for R&D in clean sectors, but recent research suggests that this alone is insufficient for transitioning to clean energy systems quickly: the optimal policy path relies heavily on subsidies for research (in addition to carbon taxes), with immediate and large R&D subsidies that decrease over time (Acemoglu et al., 2012; Acemoglu et al., 2016).

To this end, twenty-two countries and the European Union have committed to double public R&D spending on clean energy innovation by 2021 through "Mission Innovation" (Mission Innovation, n.d.). Our calculations presented in the next section suggest that this is still below optimal levels, and the success or otherwise of the spending is likely to have a significant impact on the cost of meeting the climate change challenge. Equally important is how governments choose to design support mechanisms and policy portfolios. Increases in R&D spending alone do not guarantee successful innovation outcomes. Resources must be spent *wisely* if they are to achieve the desired innovations, and this is especially so if the R&D spending pledges are not met.

Policy design should be based on the best evidence of what works, and why, so that scarce resources are not wasted. Nevertheless, how to most effectively drive innovation with public spending is still not well understood. This may seem remarkable given the long history of governments subsidizing energy innovation activities like R&D with tax incentives, direct grants, and deployment subsidies. Methodological and data limitations, however, often present challenges that make it difficult to draw causal links between mechanisms and outcomes. A few recent papers overcome some of these barriers, such as Dechezleprêtre et al. (2016), Popp (2016), and Howell (2017). Further analyses like these are needed to enhance the evidence base for innovation policy design.

In this Perspective, we first discuss why economic theory justifies government-funded support for R&D and offer new insights into the appropriate level of funding for clean energy R&D (section II). We then focus on what is known (and not known) about innovation policy effectiveness and identify four key methodological challenges that must be addressed for researchers to better provide evidence to policymakers on innovation policy effectiveness (section III). We argue that randomized control trials (RCTs) can be a valuable tool for evaluating innovation policy design (section IV), and we conclude (section V) by presenting a set of policy priorities for generating a wider body of evidence on which innovation policies work and why.

II. What is the optimal level of government-funded R&D?

Without government intervention, competitive markets under-incentivize private investment in the development and diffusion of new technologies, and more generally, under-supply innovative activity (Nelson, 1959; Arrow, 1962). Society accumulates large knowledge spillovers from R&D, so firms do not appropriate the full benefits associated with their innovations (Jaffe et al., 2005). This creates a wedge between the social and private benefits of innovative activity that policy should eliminate.

This gap between the social and private benefits of innovation can be quite large. Studies examining the returns to R&D tend to find marginal social rates of return that are at least double private marginal rates of return from investments, with social returns often estimated to be about 30 to 50 percent per dollar spent on R&D (Hall et al., 2010). Knowledge spillovers are particularly high for low-carbon technologies relative to high-carbon technologies, most likely because they are novel with high marginal returns to first movers (Dechezleprêtre et al., 2015). Clean electricity technologies induce approximately 20 percent more knowledge spillovers than average innovations, whereas dirty electricity technologies lag behind average innovations (Dechezleprêtre et al., 2015). This wedge between the social and private benefits for clean energy innovation is widened even further due to environmental externalities, and the optimal level of public expenditures on research subsidies theoretically should equal the size of external spillovers (Goulder and Schneider, 1999).

It is argued that a global commitment to clean energy R&D is needed (Georgeson et al., 2016) and current global spending on clean energy R&D is insufficient (Margolis and Kammen, 1999; IEA, 2015; Chan and Anadón, 2016; Maragoni et al., 2017; Anadon et al., 2017). But by how much? Our simple calculations suggest the need for ramping up government R&D spending by more than fivefold. Consider the United States, for example. Fischer et al. (2017) develop a stylized two-stage model that incorporates knowledge spillovers (among other things) to assess policy mixes for reducing carbon emissions. Investments in R&D and learning-by-doing are made in the first stage of the model and resulting innovations are used in the second stage. When applying the model to the U.S. electricity sector, and assuming cumulative emissions between 2015 and 2040 must be reduced by 40% compared to business-as-usual, the authors find that the optimal policy entails spending 25% of solar generation revenues on solar R&D subsidies and 12% of wind/other revenue generation for wind R&D and other more conventional renewable energy resources (excluding hydropower) on research subsidies (see Table 3 of Fischer et al. (2017)).

Our own calculations based on 2016 net generation and average electricity price data from the U.S. Energy Information Administration indicate that these findings imply that U.S. government clean energy R&D spending should be about $5.2 billion, comprising $3.8 billion on wind/other R&D subsidies and $1.4 billion on solar R&D subsidies. By comparison, others have estimated that actual U.S.

government spending on renewable energy R&D in 2016 was only $1.0 billion (FS-UNEP, 2017). If these numbers are correct, government support should increase by roughly five times current levels. This increase perhaps should occur gradually in order to avoid high adjustment costs, however recent evidence suggests that adjustment costs may not be a pressing concern considering current levels of public energy R&D support (Popp, 2016).

We considered other analyses in attempt to falsify this conclusion. For example, Chan and Anadón (2016) examine optimal energy R&D portfolios for the U.S. and suggest a 10-fold expansion in annual R&D budgets for utility-scale spending on various energy technologies compared to 2012 levels. The results are justified by returns to economic surplus, with energy storage and solar PV exhibiting the greatest returns to public R&D investment. The authors also note that the current allocation of energy R&D funds is far from optimal. There is little evidence for diminishing returns to energy R&D at current funding levels across OECD countries – productivity of spend has not declined – providing another reason to think that an expansion of energy R&D budgets is unlikely to be wasteful (Popp, 2016). The key takeaway from this set of literature as a whole is that there appears to be evidence supporting substantial increases in public R&D funding for clean energy innovation, with gradual and continuous increases until the returns to R&D no longer justify the public investment.

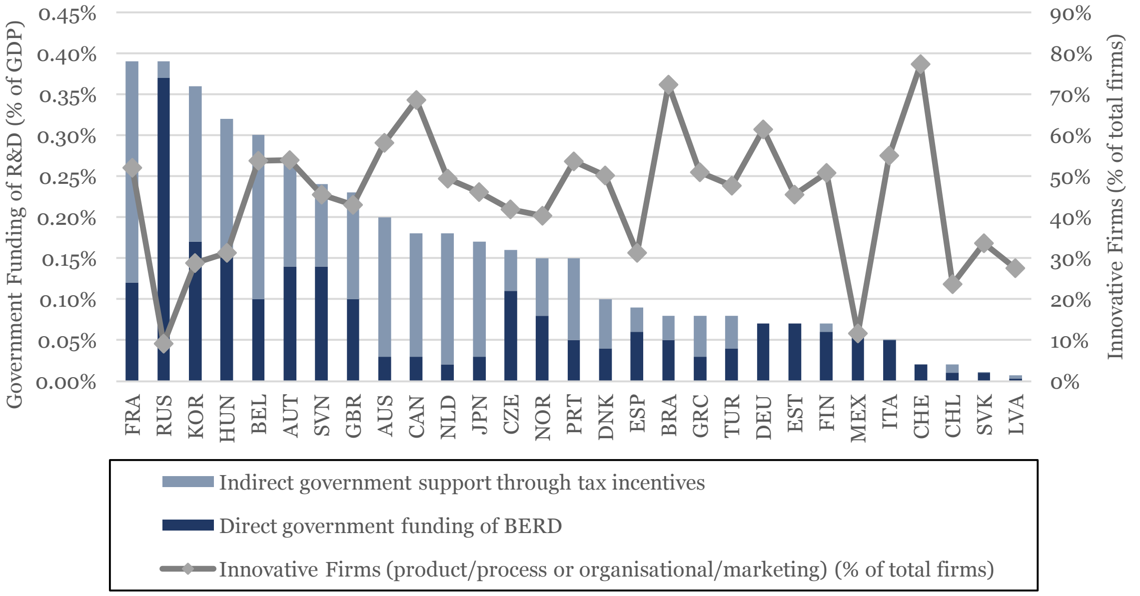
Historic spending on clean energy R&D subsidies, as opposed to technology deployment subsidies, is also strikingly unbalanced in many regions. Some countries in Europe have invested heavily in deployment policies such as feed-in tariffs (FiTs) but have committed (relatively) little resources to R&D—in many cases much less than half the spend on deployment, such as in Germany where market support for solar PV has exceeded public R&D funding by a factor of 120 (Hoppmann, 2015)—whereas research suggests that the balance should be much closer to one-to-one (Fischer et al., 2017).

There is a clear need to enhance clean energy R&D public support, however it is important to remember that doing so does not guarantee immediate innovation success. Spending resources wisely is equally important. This requires careful examination of how different mechanisms impact innovation outcomes, using methods that allow for causal interpretation, which we discuss in the next section.

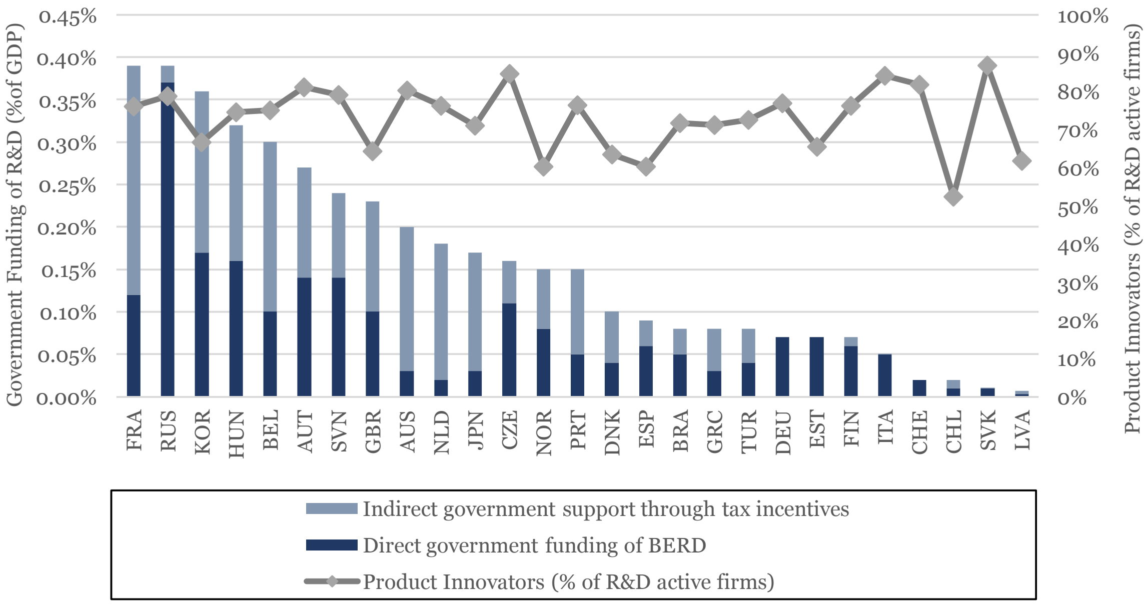
III. What are the barriers to understanding R&D support effectiveness?

Public funding makes it cheaper for firms to conduct R&D, but resources must be allocated to support schemes that are effective, and understanding which mechanism designs work best and why is not trivial. Furthermore, it may take several years for the impact of support expansion to be realized (Popp, 2016). It is not that increasing overall support is ineffective; indeed, Bloom, Griffith, and Van Reenen (2002) show that there are positive effects of R&D tax credits at the country level (for all R&D) on R&D intensity, and firms performing R&D are in turn more likely to innovate (OECD, 2015). However, it is critical to consider policy design when implementing new support schemes.

Consider Figure 1, which plots total government spending of R&D – not just for energy – as a percentage of GDP by country (split between direct and indirect support) against "innovative" firms. Panel A defines innovative as the percentage of total firms reporting product/process or organizational/marketing innovations in national community innovation surveys and reported in the 2015 OECD Innovation Indicators database. Panel B defines "innovative" as the percentage of only firms that are R&D active reporting product innovations in national innovation surveys.



Panel A: Percentage of total firms that reported product/process or organizational/marketing innovations



Panel B: Percentage of R&D active firms that reported product innovations

Figure 1: Government Funding for Business R&D and Innovative Firms

Figure Note: Direct government funding of business R&D (BERD) and tax incentives for R&D are 2014 figures from the OECD R&D Tax Incentive Indicators (Main Science and Technology Indicators). Innovative firms are defined as those reporting having completed product, process, organisational, or marketing innovations as defined by the 2015 OECD Innovation Indicators, a database that compiles information from national community innovation surveys.

The message is anything but clear and a number of questions arise. Some countries allocate relatively large proportions of their budgets to business R&D yet have a lower proportion of total firms reporting innovations than other countries that spend relatively little. There is also substantial variation in the allocation of funds between indirect versus direct support, yet there does not appear to be a close connection to innovation outcomes, at least not when R&D and innovation are measured in these ways.

Again, this is not to argue that increasing R&D support is ineffective, but rather that there is no clear, linear relationship between increased R&D spending (in total), or the allocation between direct and indirect support, and the proportion of firms that report producing innovations. Spending resources wisely and designing programs carefully is equally as important as spending a great deal, as is accounting for details such as innovation outcome measurement and timing nuances when studying policy effectiveness and informing R&D support allocation decisions.

Government subsidies for R&D can take on many forms, from direct grants that target specific technologies and sectors where intervention is in high demand, to tax credits that reduce the cost of private R&D and which can address firm selectivity. There are also many policy design options. Governments can hold competitions or favor collaborative innovation platforms, and R&D tax credits can be volume-based, incremental, or both. Certain policy designs may benefit different types of firms, which in turn may determine the types of innovations that result. Despite recent advances in the literature (discussed in this section), there are still gaps to close. At least four key challenges must be overcome—which have been addressed in some studies already—for economics research to provide more evidence on innovation policy effectiveness, which we describe in this section and summarize in Table 1.

3.1. Measuring Innovation Outcomes

So far, a rich literature studies the impacts of public R&D support on private firm R&D expenditures (i.e., input additionality)—such as Bloom et al. (2002), Duguet (2012), Lokshin and Mohnen (2012), and others—but less is known about how it stimulates productivity outputs and innovation. Studying the effects of R&D support on output additionality requires accurately measuring innovation. This is inherently difficult, as both incremental advances and technological breakthroughs are highly uncertain and depend on intangible factors such as management quality and business culture.

Some research uses patents or paper citations as proxies (e.g., Johnstone et al., 2010; Popp, 2016; Dechezleprêtre et al., 2016). These are important contributions to the literature. At the same time, these proxies arguably reflect intermediary outputs as opposed to final goods and services innovations. Patents may signal that a company has potentially valuable assets, but there is no guarantee that they lead to technology development and deployment. They are obtained to protect certain intellectual property (IP) and do not measure innovations that actually emerge from the IP. It is unclear whether patents even encourage innovation activity more generally. Lerner (2009) finds no positive impact on innovation of strengthening patent protection, and the effect even could be negative. Qian (2007) also finds that patent protection alone does not stimulate domestic innovation, however it can make a contribution in some relatively rich countries. The role of patents also varies across industries (Orsenigo and Sterzi, 2010) and thus the degree to which patenting proxies for innovation is heterogeneous and sector-specific.

Additional measures of firm-level innovation can improve this literature. Some options include firm-level indicators of success, such as cost reductions, performance improvements, innovation capability improvements, and process efficiency gains. Novel use of productivity outcomes like whether firms secure venture capital funds and other firm performance measures are starting to emerge (e.g., Howell (2017), Einiö (2014), Czarnitzki et al. (2011), and Colombo et al. (2011)).

3.2. Estimating Causal Effects

Understanding which policies and interventions work—or work better—requires the use of research designs that allow for causal inference. In other words, it requires estimating the difference between actual outcomes after receiving public support and the potential outcomes that would have occurred without receiving support, which can be inferred using regression methods. This is not easy, however. Policy changes often coincide with unobserved factors that could influence innovation activities. The direction of causality between incentive and outcome is ambiguous: firms' R&D investment decisions are influenced by government policies, but at the same time, governments may introduce policies because of low innovation activity. Studies of R&D support also often suffer from selection bias (i.e., the fact that some firms – such as those that are already more innovative –are more likely to win grant competitions, for instance, biasing a direct comparison to non-grant recipients). All of these challenges make it difficult to estimate how a policy or funding support impacts innovation outcomes.

There are methods for overcoming these challenges, such as the use of instrumental variables methods, quasi-experiments, and RCTs (e.g., see Athey and Imbens (2017a) for an overview of strategies used in economics for identifying causal effects). Some examples where such methods have been applied to study innovation include Hall (1993) and Bloom et al. (2002) who use instrumental variables, and Bronzini and Iachini (2014), Agrawal et al. (2014), Dechezlepretre et al. (2016), and Howell (2017) who use quasi-experiments. The use of RCTs has been uncommon in the innovation literature so far, which we discuss further in Section IV.

3.3. Understanding Policy Interactions

Accounting for policy interactions is important for knowing whether the independent effects of each instrument are crowded out and for assessing whether complementarities create additional benefits. Funding mechanisms for clean energy R&D can also interact with policies addressing environmental externalities. Empirical research tends to focus on just a single instrument at a time, primarily because it is uncommon for different R&D support schemes and policies to co-exist and to be implemented in a way that allows for disentangling both their independent and interaction effects.

A critical area for continued investigation therefore is policy instrument choice when there are multiple policies and market failures interacting (Goulder and Parry, 2008). Some studies, mostly using simulation methods, have started to address these questions. Fischer and Newell (2008) and Fischer et al. (2017) develop models to assess different policies for reducing carbon emissions and promoting innovation and diffusion of renewable energy. They find that the optimal policy includes many policy instruments, including R&D support and emissions pricing, but the papers do not examine how such interactions impact innovation outcomes. There are a few related empirical studies (e.g., Hægeland and Møen, 2007; Falk et al., 2009) but they suffer from some of the other barriers discussed in this section.

3.4. Accounting for Response Timing Lags and Uncertainty

A final challenge is the time lag between research support and commercial outcomes. This makes it difficult to measure the final impacts of support schemes (Popp, 2016). Recent work has shown that up to a decade is needed to realize the full effect of public energy R&D funding. After funding is received, the first new related patent applications typically appear within about one year, but further such related applications continue for roughly another 13 years (Popp, 2016). Studies that do not account for this time lag may not fully capture policy effects. Overcoming this requires tracking innovation outcomes over long time series.

Table 1: Top Four Barriers to Measuring Innovation Policy Effectiveness

Challenge	Description	Solutions
1. Measuring Innovation Outcomes	Measuring innovation outcomes is non-trivial and required data are often difficult to access.	Develop new measures of innovation that can be tracked consistently over time, such as metrics that capture technology development and cost reductions. Improve access to such measures.
2. Estimating Causal Effects	The direction of causality between funding support and innovation is not always clear.	Employ research designs such as experimental, quasi-experimental, or instrumental variable approaches, which could include working with policymakers to embed experiments into policy and incentive design or conducting randomized control trials (RCTs).
3. Understanding Policy Interactions	Policies and funding mechanisms could have interactive effects.	Identify empirical settings or conduct experiments in which more than one mechanism can be studied simultaneously.
4. Accounting for Response Timing Lags and Uncertainty	There is uncertainty in the length of time required to produce measurable innovation outcomes after receiving research support.	Account for significant time lags and conduct sensitivity analysis regarding lag length, which can require data spanning many years.

IV. A Call for Randomized Control Trials in Innovation Studies

Perhaps the most important barrier to developing a wider evidence base of innovation policy effectiveness is estimating the causal effects of interventions and support mechanisms. Descriptive analyses that reveal correlations between inputs like R&D support and outputs like innovations are useful and warrant further investigation, but different tools are required for identifying the direct causal impact of an intervention. It is often difficult to find suitable instrumental variables for addressing endogeneity concerns, and quasi-experiments are rare in practice.

Randomized control trials (RCTs) are an attractive alternative, avoiding many of the challenges associated with causal inference that are often faced in observational studies (e.g., see Athey and Imbens (2017b) for a few classic examples of RCTs and on the econometrics of randomized experiments), and they offer tremendous potential for informing innovation policy design. If implemented appropriately, they can provide insight not only on whether an intervention works, but also the drivers of success, which allows researchers to uncover *why* mechanisms work in certain contexts and not others. The effects of specific components and characteristics of support mechanisms can be teased out, and selection bias can be eliminated so that clear conclusions about support effectiveness can be made. While RCTs—often referred to as the gold standard for causal inference—are now increasingly common in other fields of economics (e.g., see Duflo, Glennerster, and Kremer (2006) for a survey of RCTs in development economics), their application in the study of innovation so far has been relatively limited.

RCTs could be employed in several different ways to study innovation. For instance, specific requirements placed upon grant award recipients, such as collaboration with other firms or universities, and other features of the support mechanism could be randomly assigned to grant recipients. Research using RCTs to study industrial or innovation policy is starting to emerge, and the UK has even launched an Innovation Growth Lab to specifically support experiments that address innovation and growth policy. Several innovation-related RCTs are now underway, addressing questions related to how proximity impacts collaboration and knowledge generation, how different types of knowledge transfer impact business-science interactions, how incubator spaces impact startup performance and survival, and more (IGL, 2017).

V. Policy Priorities for Evidence-Based Innovation Policy

In this Perspective, we provided insights into two of the most important questions in energy innovation policy today: 1) the optimal level of government-funded R&D support for clean energy innovation, and 2) barriers to designing evidence-based innovation policy instruments. There are three broad conclusions.

First, the optimal public support for energy R&D is well above current levels—it should increase, as swiftly as reasonable but while also accounting for adjustment costs, by perhaps a factor of five. While government commitments to double public R&D spending on clean energy innovation through "Mission Innovation" should be applauded, this paper suggests that another round of funding increases must be agreed.

Second, there is increasing evidence that government-funded R&D fiscal incentives and direct grants can drive innovation. Such mechanisms, and their detailed design, deserve further consideration, as appropriate innovation policy design is context-specific and depends on the relative intensity of market failures associated with knowledge spillovers and environmental externalities. For example, in certain contexts, grants for small businesses that are capital constrained could be most effective if allocated to more numerous, small, early-stage grants while prioritizing younger firms and first-time applicants (Howell, 2017). Our understanding of how to best design R&D support can be enhanced by continued examination of what works in certain contexts and why.

Generating a wider body of robust evidence on innovation policy effectiveness will require overcoming key methodological challenges, including: 1) measuring innovation outcomes in new and consistent ways, 2) identifying the *causal* effects of R&D public support mechanisms on innovation outcomes, 3) examining how policies interact, and 4) accounting for time lags between receiving research support and commercial success. Removing barriers that contribute to these challenges could enable researchers to marshal empirical evidence on innovation policy effectiveness, which is critically urgent for delivering a net-zero-carbon energy system.

The third and perhaps most important policy recommendation of this paper therefore is that governments and policymakers can help improve our understanding of innovation policy effectiveness by working with researchers to remove these barriers. At the least, this involves enhanced access to data on the use and costs of R&D support programs (both for successful and non-successful applications), along with firm-level data on R&D inputs, innovation outputs, and performance. Developing improved measures of innovation outcomes and consistently tracking them over time would also help enormously, as would finding appropriate ways to manage legal restrictions that prevent researchers from matching relevant datasets on research funding and performance. Ideally, policymakers can encourage and support implementation of innovation randomized control trials (RCTs), or work with researchers to embed experiments into policy and incentive designs. Doing so is essential for establishing a causal link between policy and innovation outcomes.

References

Acemoglu D., Aghion P., Bursztyn L., and Hemous D., 2012. "The environment and directed technical change," *The American Economic Review,* 102(1): 131-166.

Acemoglu D., Akcigit U., Hanley D., and W. Kerr, 2016. "Transition to clean technology", *Journal of Political Economy*, 124(1): 52-104.

Agrawal A., Rosell C., and T.S. Simcoe, 2014. "Do tax credits affect R&D expenditures by small firms? Evidence from Canada," NBER Working paper 20615.

Anadón, L.D., Sims Gallagher, K., and Holdren, J.P., 2017. "Rescue US energy innovation," *Nature Energy*

Arrow, K.J., 1962. "The Economic Implications of Learning by Doing," *Review of Economic Studies,* 29: 155-173.

Athey S., Imbens G.W., 2017a. "The State of Applied Econometrics: Causality and Policy Evaluation," *Journal of Economic Perspectives,* 31(2), pp. 3-32.

Athey S., Imbens G.W., 2017b. "Chapter 3 – The Econometrics of Randomized Experiments," *Handbook of Economic Field Experiments,* 1, pp. 73-140.

Bloom N., Griffith R., and J. van Reenen, 2002. "Do R&D Tax Credits Work? Evidence from a Panel of Countries 1979-1997," *Journal of Public Economics*, 85(1), 1-31.

Bronzini R. and E. Iachini, 2014. "Are Incentives for R&D Effective? Evidence from a Regression Discontinuity Approach," *American Economic Journal: Economic Policy,* 6(4), 100-134.

Chan G. and L.D. Anadón, 2016. "Improving Decision Making for Public R&D Investment in Energy: Utilizing Expert Elicitation in Parametric Models," EPRG Working Paper 1631, Cambridge Working Paper in Economics 1682.

Colombo M.G., Grilli L., and Murtinu S., 2011. "R&D Subsidies and the Performance of High-Tech Start-Ups," *Economics Letters,* 112, 97-99.

Covert T., Greenstone M., Knittel C.R., 2016. "Will We Ever Stop Using Fossil Fuels?" *Journal of Economic Perspectives,* 30(1), pp. 117-138.

Czarnitzki, D., Hanel, P., and Rosa, J. M., 2011. "Evaluating the Impact of R&D tax Credits on Innovation: A Microeconometric Study on Canadian Firms," *Research Policy*, 40(2): 217–229.

Dechezleprêtre, A., Martin, R., and Mohnen, M., 2015. Knowledge spillovers from clean and dirty technologies. Grantham Research Institute on Climate Change and the Environment Working Paper 135.

Dechezleprêtre A., Einiö E., Martin R., Nguyen K-T., and Van Reenen J., 2016. "Do Tax Incentives for Research Increase Firm Innovation? An RD Design for R&D", CEP Discussion Paper No 1413.

Duflo E., Glennerster R., Kremer M., 2016. "Using Randomization in Development Economics Research: A Toolkit," *Handbook of Development Economics,* Elseviers.

Duguet E., 2012. "The Effect of the Incremental R&D Tax Credit on the Private Funding of R&D: An Econometric Evaluation on French Firm Level Data," *Revue d'économie politique*, 122, pp. 405-435.

Einiö E., 2014. "R&D subsidies and company performance: Evidence from geographic variation in government funding based on the ERDF population-density rule," *Review of Economics and Statistics,* 96(4) 710-728.

Falk R., Borrmann J., Grieger N., Neppl-Oswald E., and U. Weixlbaumer, 2009. "Tax Incentive Schemes for R&D," Part 4 of the Evaluation of Government Funding in RTDI from a Systems Perspective in Austria, Vienna: Austrian Institute for Economic Research.

Farmer J.D. and F. Lafond, 2016. "How predictable is technological progress?" *Research Policy*, 45(3): 647-665.

Fischer C. and R.G. Newell, 2008. "Environmental and technology policies for climate mitigation," *Journal of Environmental Economics and Management,* 55(2), pp. 142-62.

Fischer C., Preonas L., and Newell R., 2017. "Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many?" *Journal of the Association of Environmental and Resource Economists.*

FS-UNEP, 2017. "Global Trends in Renewable Energy Investment 2017," Frankfurt School FS-UNEP Collaborating Centre for Climate & Sustainable Energy Finance, UN Environment and Bloomberg New Energy Finance. Available at: http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf.

Georgeson L., Maslin M., and Poessinouw M., 2016. "Clean up energy innovation," *Nature* 538: 27-29.

Goulder L.H. and I. Parry, 2008. "Instrument Choice in Environmental Policy," *Review of Environmental Economics and Policy,* 2(2), pp. 152-74.

Goulder L.H. and S.H. Schneider, 1999. "Induced Technological Change and the Attractiveness of CO2 Abatement Policies," *Resource and Energy Economics,* 21, pp. 211-52.

Hall B.G., Mairesse J., and P. Mohnen, 2010. "Measuring the Returns to R&D," in: Handbook of the Economics of Innovation, Elsevier, pp. 1033-1082.

Hall B.H., 1993. "R&D Tax Policy During the Eighties: Success or Failure?" *Tax Policy and the Economy*, 7, pp. 1-36.

Hægeland T. and J. Møen, 2007. "The Relationship Between the Norwegian R&D Tax Credit Scheme and Other Innovation Policy Instruments," Reports 2007/45, Statistics Norway: Oslo.

Hoppmann J., 2015. "The Role of Deployment Policies in Fostering Innovation for Clean Energy Technologies: Insights From the Solar Photovoltaic Industry," *Business & Society*, 54(4), pp. 540-558.

Howell S., 2017. "Financing Innovation: Evidence from R&D Grants", *The American Economic Review.*

IEA, 2015. *Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action,* International Energy Agency, Paris: France. Available at: http://www.iea.org/bookshop/710-Energy_Technology_Perspectives_2015.

Innovation Growth Lab (IGL), 2017. Available at: http://www.innovationgrowthlab.org/our-projects.

Jaffe A.B., Newell R.G., Stavins R.N., 2005. "A tale of two market failures: Technology and environmental policy," *Ecological Economics,* 54, pp. 164-174.

Johnstone, N., I. Haščič and D. Popp, 2010. "Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts", *Environmental and Resource Economics*, 45, pp. 133-155.

Lerner J., 2009. "The Empirical Impact of Intellectual Property Rights on Innovation: Puzzles and Clues, *American Economic Review: Papers & Proceedings,* 99:2, pp. 343-348.

Lokshin B. and P. Mohnen, 2012. "How effective are level-based R&D tax credits? Evidence from the Netherlands," *Applied Economics,* 44(12), 1527-1538.

Maragoni G., De Maere G., Bosetti V., 2017. "Optimal Clean Energy R&D Investments Under Uncertainty," FEEM Working Paper 16.2017. Available at: https://www.econstor.eu/bitstream/10419/162258/1/NDL2017-016.pdf.

Margolis R.M., Kammen D.M., 1999. "Underinvestment: the energy technology and R&D policy challenge," *Science* 285, pp. 690-692.

Mission Innovation, n.d. Website: http://www.mission-innovation.net

OECD, 2015. *OECD Science, Technology and Industry Scorecard 2015: Innovation for growth and society,* OECD Publishing, Paris. http://dx.doi.org/10.1787/sti_scoreboard-2015-en

Orsenigo L. and V. Sterzi, 2010. "Comparative Study of the Use of Patents in Different Industries," Bocconi University, Knowledge, Internationalization and Technology Studies, Working Paper n. 33/2010.

Nelson, R.R., 1959. "The Simple Economics of Basic Scientific Research," *Journal of Political Economy,* 297-306.

Pfeiffer A., Millar R., Hepburn C., and Beinhocker, E., 2016. "The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy," *Applied Energy* 179: 1395-1408.

Popp D., 2016. "Economic analysis of scientific publications and implications for energy research and development," *Nature Energy* 1, 16020.

Qian Y., 2007. "Do National Patent Laws Stimulate Domestic Innovation in a Global Patenting Environment? A Cross-Country Analysis of Pharmaceutical Patent Protection, 1978-2002," *Review of Economics and Statistics,* 89(3), pp. 436-53.