PRODUCING AND STEERING RESEARCHERS

Eugenie Dugoua* Todd Gerarden† Kyle Myers‡ Jacquelyn Pless§

Extended Abstract

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Technological change has long been recognized as central to enhancing living standards and driving economic growth (Aghion and Howitt 1992; Romer 1990). But as the full social value of discoveries and inventions are rarely, if ever, captured by their creators, private markets tend to under-provide innovative activity. This phenomenon is most frequently appreciated in the context of firms' innovation decisions, as imperfect appropriability can dampen the incentives for firms to invest in research and development (R&D). It also applies, though, to the supply of researchers—those producing the knowledge upon which inventions are built—and their decisions to enter the market for ideas in the first place.

Yet most policies focus on providing incentives to firms to invest in innovative activity rather than creating scientific human capital (Van Reenen 2021). Governments frequently offer direct grants and tax credits that reduce the cost of investing in R&D, and there is growing evidence that these incentives enhance innovative activity.[1] An implicit assumption behind these policies is that more innovation by firms may increase the demand for inventors and lead to more individuals engaging in innovative activity. However, if the supply of inventors is inelastic, these demand-side policies will just increase the wages of high-skilled workers (Goolsbee 1998). The supply of inventors could be inelastic in the short run due to frictions in higher education (Romer 2000). Human capital policies may therefore be the most direct mechanism for increasing the supply of inventors (Bloom, Van Reenen, and Williams 2019; Van Reenen 2021). After all, reaching the

*e.dugoua@lse.ac.uk. Department of Geography and Environment, London School of Economics.
†gerarden@cornell.edu, Cornell Dyson School of Applied Economics and Management
‡kmyers@hbs.edu, Harvard Business School
§jpless@mit.edu, MIT Sloan School of Management

1. See Bloom, Van Reenen, and Williams (2019) for a review of this literature.

frontier of knowledge and producing new ideas typically relies upon significant education and training. But providing financial incentives for entry into the market for ideas may have limited benefits if the supply of researchers and potential inventors is also inelastic.

In this paper, we study how human capital policy affects the quantity of researchers. We do so by estimating the effect of funding from the U.S. Department of Energy (DOE) allocated to different energy technologies on the production of dissertations associated with those technologies. The energy sector is a particularly interesting sector from an economic perspective because unpriced externalities create a wedge between the private and social benefits of scientific advances. We explore this further by examining the *direction* of their research given how this wedge varies across technologies, and thus inducing scientists to pursue topics with the greatest potential value for society might require a disproportionate amount of funding. Increasing the supply of energy inventors is also particularly important and timely for policy, as accelerating and steering innovation towards clean technologies will be critical for addressing climate change.

Quantifying the impacts of government funding on the supply of inventors is empirically challenging for several reasons. First, standard measures of the number of inventors—such as authors of patents—do not capture the supply of *potential* inventors, as individuals may engage in innovative activity without yet successfully innovating. In other words, there is an unobserved component of supply. Quantifying the direction of that activity compounds this challenge. Identifying the causal drivers of researchers' decision-making is then complicated by the self-selection into becoming a researcher, and the selection into research areas also can be endogenously driven by opportunities or other unobserved factors.

We overcome these challenges by building a novel data set of PhD dissertations produced by U.S. higher education institutions and exploiting quasi-experimental variation in government funding. Studying dissertations provides economic and econometric advantages. One economic advantage is that it allows us to observe inventors' extensive margin choices to specialize in a particular field rather than how they respond on the intensive margin (by switching specializations after they have already committed to one). At the same time, not all individuals completing a PhD in an innovation-oriented field actually become inventors, so dissertations reflect human capital accumulation, which can be thought of as the supply of *potential* inventors. We thus also provide evidence that dissertations are an important measure of the supply of *actual* inventors by showing that a larger stock of dissertations is correlated with the flow of new patents within a given technology area, state, and year.[2] From an econometric perspective, an advantage of studying dissertations is that we can apply text analysis to yield data with rich variation across technologies, institutions, and time.

More specifically, we begin by gathering data from the ProQuest Dissertations and Theses Global Database, which contains dissertations from all disciplines across 2,315 institutions in 96 countries. We focus on the U.S., as this is our empirical setting, and gather data from 1980 to 2020. We use subject terms, paper keywords, and paper categories to identify disciplines. To identify energy-specific dissertations, we construct a dictionary of terms specific to different energy types such as "solar panel" and "photovoltaic" for solar energy. We then search for these terms in each dissertation's title, abstract, and other metadata. We count the number of occurrences of each term or combination of terms in all relevant fields and define a dissertation as clean, dirty, or grey if it contains at least one of the relevant terms.

Some interesting trends emerge from the raw data that suggest an increasing focus on energy-related topics. The share of science, technology, engineering, and mathematics (STEM) dissertations associated with energy increased significantly from the 1980s to today, with a lot of the growth starting in the late 2000s. Importantly, it is not only the shares that increase but also the levels. Dissertations across all energy technologies increased, including "dirty" energy, but the number of clean energy-related dissertations experienced the most growth by far.

Next, we document the relationship between dissertation stocks and patent flows. Our goal in this exercise is not to demonstrate a causal relationship but to explore whether producing more researchers is an important factor in driving innovation in the first place. We gather patent data from PatentsView and identify energy technology-specific patents using an approach that is similar to our approach for dissertations. We aggregate the data to the state-technology-year level and estimate the relationship between patent flows and dissertation stocks in a fixed effects framework. The estimates indicate a strong correlation between patent flows and dissertation stocks. This suggests that producing PhD-level researchers is indeed an important determinant of innovation outputs.

2. In future work, we plan to use more granular linkages between dissertations and patents by improving our technological classifications and linking the dissertations and patents of individual inventors. This may also allow us to study the factors that influence whether PhD graduates with the necessary expertise to become inventors actually do so. Another potential option is to use data on scientific publications to provide a complementary measure of the innovative output that flows from PhD dissertations.

Finally, we estimate the effect of DOE funding on dissertations using variation in technology-specific funding "windfalls" from when Congress appropriates more or less than the amounts requested by the DOE. These windfalls arise because Congressional appropriations committee members have personal or local preferences or are influenced by lobbying, all of which can influence budget line items. We gather information on the DOE's funding requests and Congressional appropriations at the technology level each year to construct these windfalls. We then take a production function estimation approach in the spirit of Olley and Pakes (1996) to account for unobserved productivity at the technology-year level that is likely to bias estimates of the relationship between DOE funding and the production of dissertations. We use DOE funding requests in a control function to proxy for unobserved productivity, allowing us to estimate the causal effect of funding amounts on a range of innovation outcomes. The outcomes we study include dissertations, patents, publications, and labor market outcomes for energy researchers.

Our paper contributes to the literature on skilled labor supply by providing new evidence on the role that human capital policy plays in shaping the supply of inventors. A growing body of work is documenting how enhancing human capital through, say, the expansion of STEM education increases and directs innovation (Bianchi and Giorcelli 2020), as well as how immigrants increase innovation (Bernstein, Diamond, McQuade, et al. 2019). Perhaps surprisingly, though, there is relatively scant evidence otherwise on how to increase the quantity and quality of scientific human capital. As stated poignantly in Romer (2000), "innovation policy in the United States has erred by subsidizing the private sector demand for scientists and engineers without asking whether the educational system provides the supply response necessary for these subsidies to work." This still holds true today, and our findings start to generate some answers to this long-standing puzzle.

The findings of our paper also complement the nascent body of work examining how scientists choose topics to pursue and how the costs of switching can be high (e.g., Azoulay, Fons-Rosen, and Graff Zivin 2019; Deming and Noray 2020; Myers 2020). This literature so far has focused on how existing inventors pivot (i.e., the intensive margin). By developing and leveraging new data on PhD dissertations, we are able to study the topic choice when deciding to become an inventor (i.e., the extensive margin).

The directional component of our paper builds on a large literature in energy and environmental economics as well. There is indeed increasing evidence that demand-side mechanisms like carbon pricing induce clean energy innovation in aggregate and at the firm level (Aghion, Dechezleprêtre, Hémous, et al. 2016; Calel 2020; Calel and Dechezleprêtre 2016; Johnstone, Haščič, and Popp 2010; Newell, Jaffe, and Stavins 1999; Popp 2002, 2019).[3] However, to the best of our knowledge, we are one of the first to study investment in human capital itself and the supply of inventors. The closest paper to ours is a work in progress by Dugoua and Gerarden, who examine how demand-side intervention incentivizes existing inventors to switch from innovating in dirty technologies to clean. Relatedly, our results also have implications for directed technical change models, which have so far assumed that the elasticity of supply is fixed or inelastic (Acemoglu, Aghion, Bursztyn, et al. 2012; Acemoglu, Akcigit, Hanley, et al. 2016; Fried 2018; Lemoine 2018).

Lastly, our paper provides insight into an avenue through which policymakers can foster long-run economic growth, given the role that individuals' education choices play in creating technological opportunities (Jones 2009). Understanding how to increase the number of inventors is of first-order importance for economic policy, especially amidst the productivity growth slow-down that many developed countries have faced over the past few decades.

3. Popp (2019) provides a comprehensive review of the last decade of research on induced energy and environmental innovation.

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