Promoting Innovation on Low-carbon Technologies

David Popp

Danish Conference on Environmental Economics

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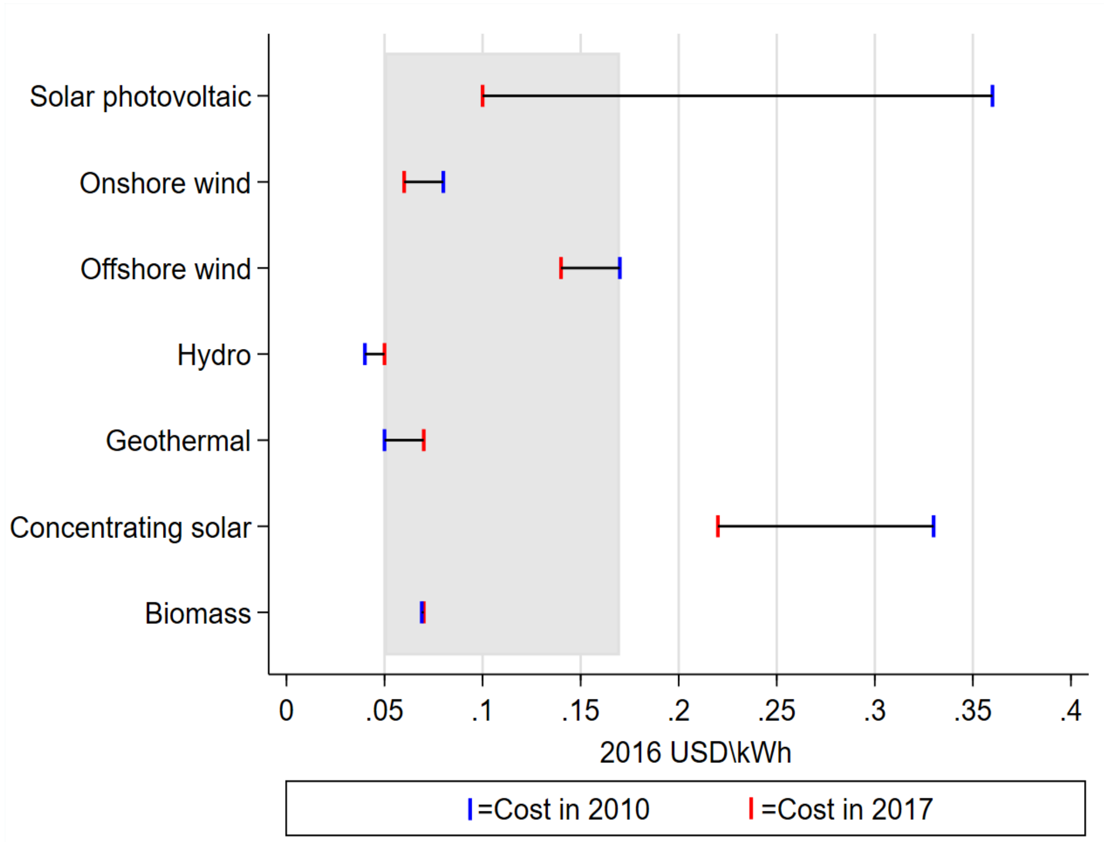
Maxwell | Syracuse University

Introduction

- Recent innovation led to historic decreases in the costs of renewable energy technologies

Levelized Cost Estimates



Source: Data from International Renewable Energy Agency, *Renewable Energy Costs in 2017.* Fossil fuel range in gray

Introduction

- Recent innovation led to historic decreases for renewable energy technologies
- As a result, use of renewables increasing rapidly

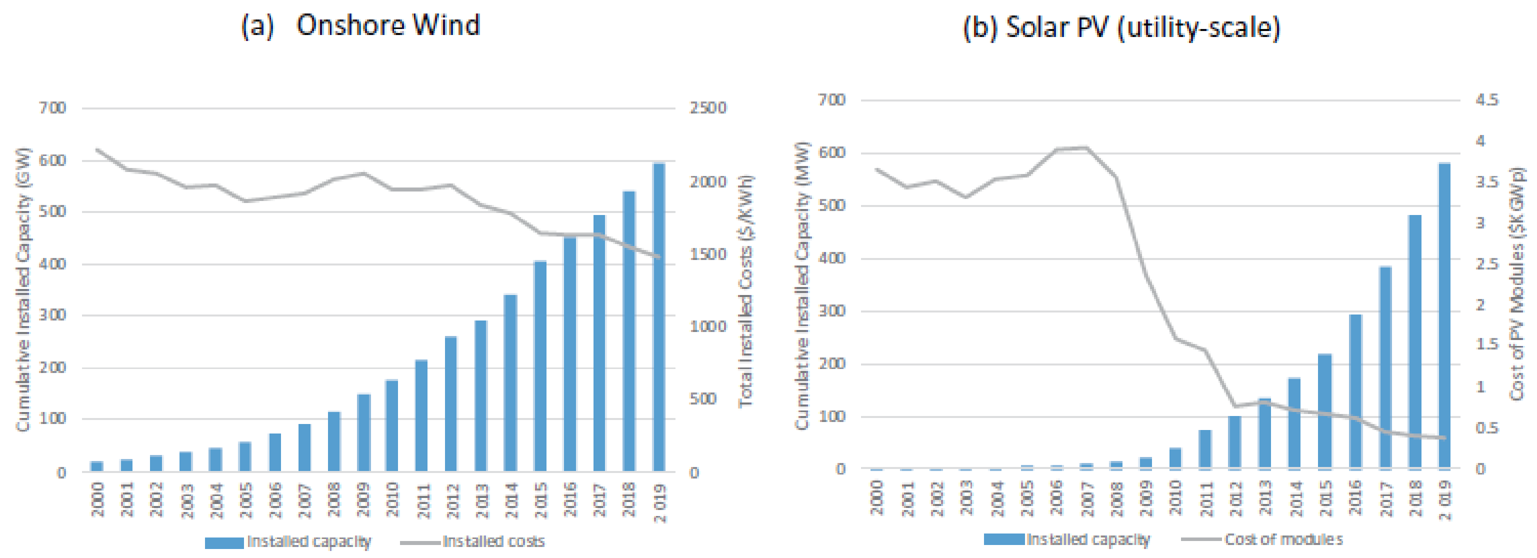


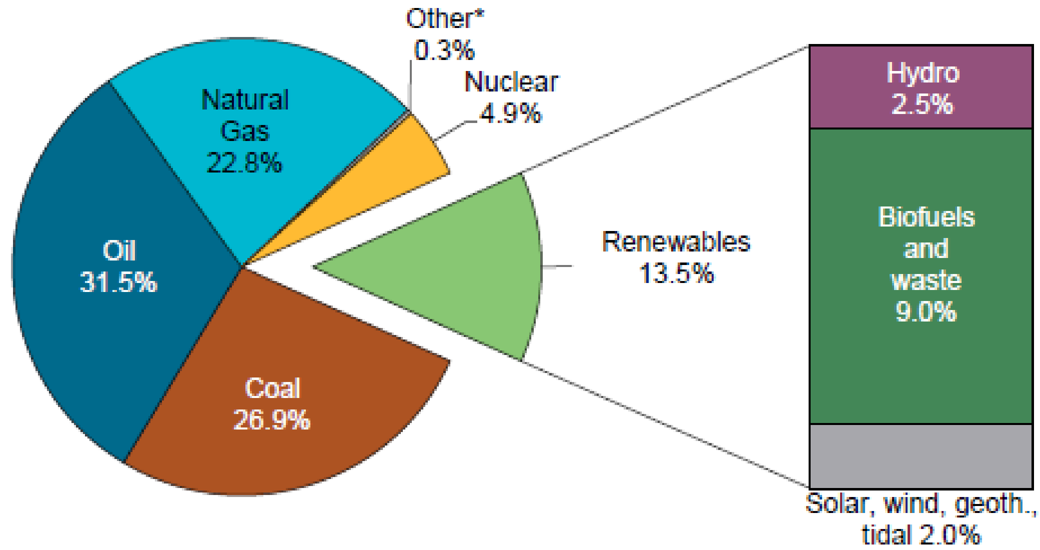
Figure 6. Evolution of global installed capacity and global weighted-average installed costs for onshore wind (panel (a)) and global installed capacity and cost of modules for utility-scale solar PV (panel (b)), 2000–2019.
Source: (Lafond *et al* 2018**, International Renewable Energy Agency (IRENA) 2020).

Source: Grubb et al., *Environmental Research* Letters (2021)

Introduction

- But there is more to be done

2018 fuel shares in world total energy supply



* Other includes non-renewable wastes and other sources not included elsewhere such as fuel cells.

Note: Totals in graphs might not add up due to rounding.

Source: IEA/OECD *World Energy Balances*.

Source: IEA Renewables Information: Overview (2020 Edition)

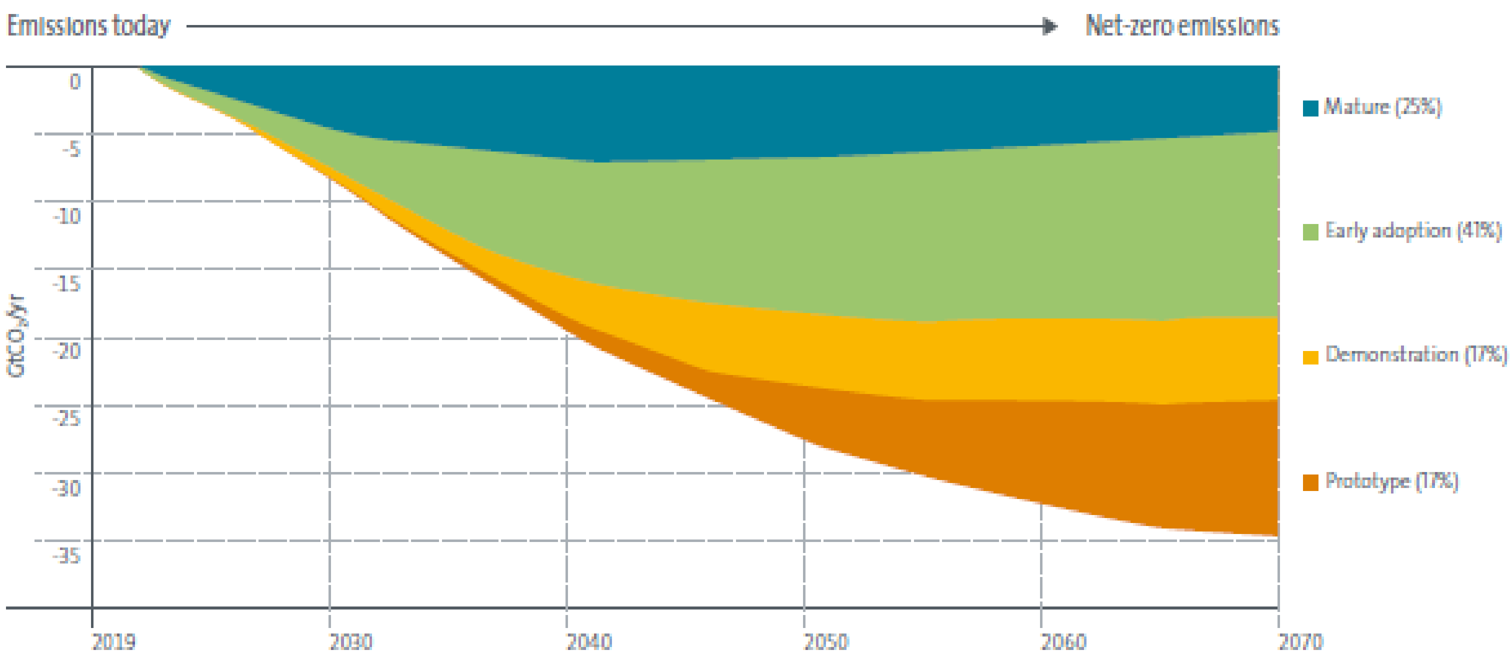
Introduction

- But there is more to be done
- Meeting increasingly ambitious climate policy goals (e.g. EU carbon neutral by 2050) requires replacing vast amounts of fossil fuel energy sources with alternative, carbon-free energy sources

Introduction

Figure 1.1

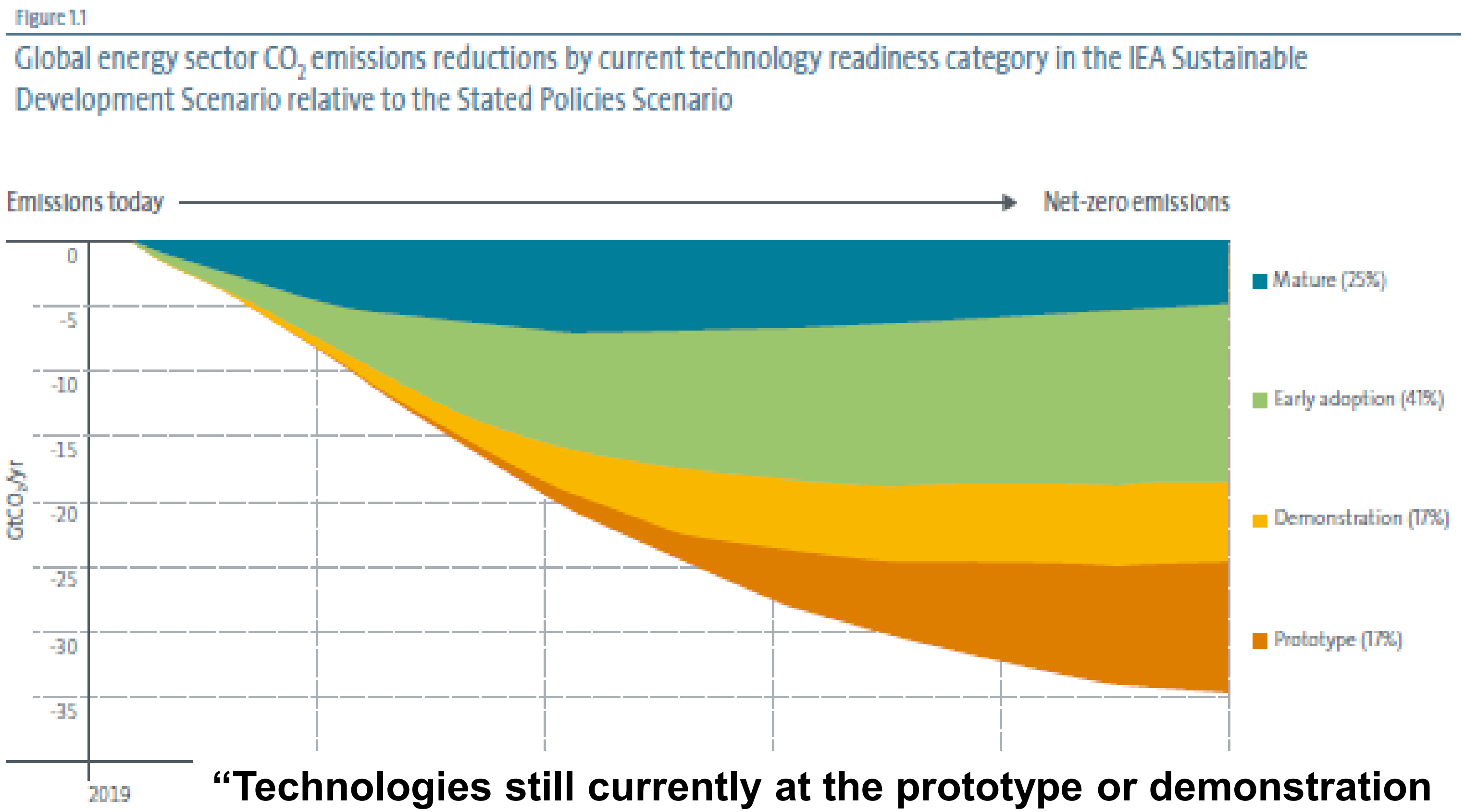
Global energy sector CO_2 emissions reductions by current technology readiness category in the IEA Sustainable Development Scenario relative to the Stated Policies Scenario



Notes: the IEA Sustainable Development Scenario maps out a way to meet the key energy-related goals of the United Nations Sustainable Development Agenda, including by mitigating climate change in line with the Paris Agreement. The trajectory for emissions in the Sustainable Development Scenario is consistent with reaching global "net-zero" CO_2 emissions by around 2070. The Stated Policies Scenario assesses the evolution of the global energy system on the assumption that government policies that have already been adopted or announced with respect to energy and the environment, including commitments made in the nationally determined contributions under the Paris Agreement, are implemented. Percentages refer to cumulative emissions reductions by 2070 between the Sustainable Development Scenario and the Stated Policies Scenario enabled by technologies at a given level of maturity.
Source: IEA 2020a: ETP Special Report on Clean Energy Innovation

Source: International Energy Agency, *Patents and the energy transition* (2021)

Introduction



"Technologies still currently at the prototype or demonstration phase represent around 35% of the cumulative CO2 emissions reductions needed to shift to a sustainable path consistent with net-zero emissions by 2070. For today's early-stage technologies to dominate their sectors by mid-century, we would require more rapid innovation cycles than in recent energy technology history."

Source: International Energy Agency, *Patents and the energy transition* (2021)

Introduction

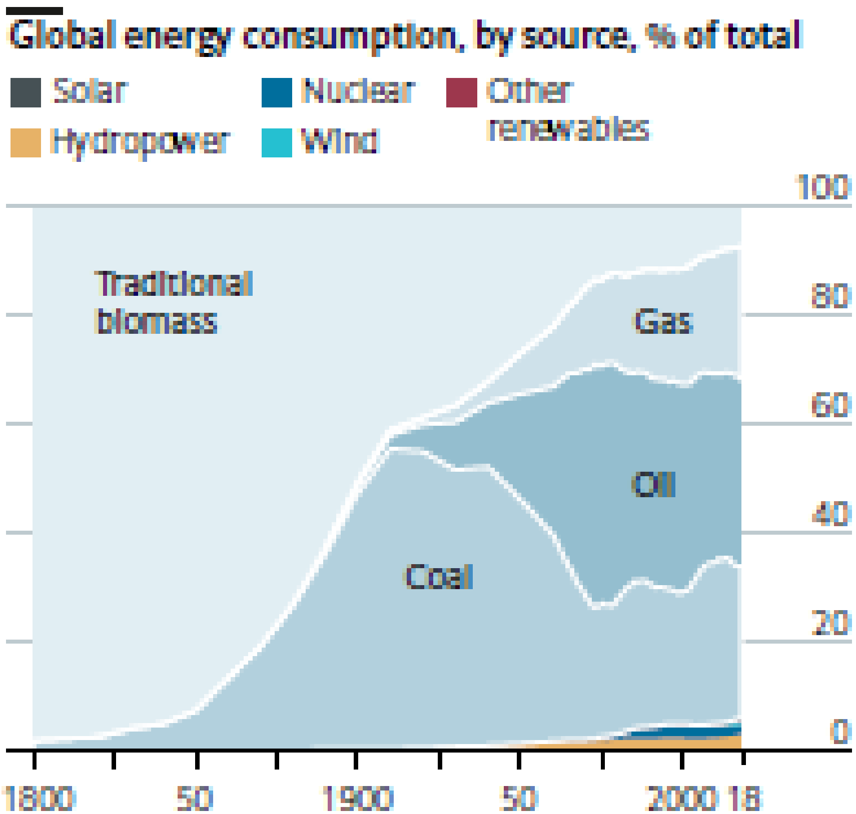
- Innovation is needed to:
  - Continue reducing the cost of existing technologies
  - Develop new breakthrough technologies
  - Develop complementary technologies (e.g. grid management, energy storage) to better integrate intermittent renewables into transmission grids

- This talk highlights key lessons from research on policy and innovation, focusing on the role of private and public sector innovation

1. Challenges to a Renewable Energy Transition
2. Measuring Environmental Technical Change
3. Clean Energy Innovation Trends
4. Technological Change & the Environment: Theory
5. The Role of Policy: Broad-based Policies
6. Targeted Policies: Which Policy Tools to Use?
7. Public Energy R&D

Challenges to a Renewable Energy Transition

- Previous energy transitions move towards fuels that are more energy dense and convenient to use
  - Wood→ coal → oil



Source: "Not-so-slow burn," *The Economist*, May 23, 2020, 49-50.

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Challenges to a Renewable Energy Transition

- Previous energy transitions move towards fuels that are more energy dense and convenient to use
  - Wood→ coal → oil

- Moving to renewables adds new challenges
  - Renewable energy must be delivered to where it is needed
    - Increased electrification is key to the renewable energy transition

Challenges to a Renewable Energy Transition

- Electricity
  - Increased electrification is key to the renewable energy transition
  - But solar and wind are intermittent
  - Possible solutions to the intermittency problem
    - Larger grids easier to balance
    - Demand-response strategies (e.g. “smart grid”)
    - Energy storage

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Challenges to a Renewable Energy Transition

- Transportation
  - Electric motors are more efficient and simpler mechanically
  - But gasoline or diesel fuel contains 40X as much energy as current batteries
    - Usable for vehicles carrying light loads and that can charge often (e.g. passenger cars)
    - Not yet viable for long-haul trucking, aviation, or maritime shipping
      - Net zero-carbon biofuels could help here
  - Consumers may not see EV as perfect substitutes for gasoline-powered vehicles (Holland *et al*. *AEJEconPol*, 2021)
    - Charging infrastructure needed

Challenges to a Renewable Energy Transition

- Industry
  - Not all processes can be electrified
  - Achieving very high heat for industrial processes such as steel, cement, and glass production is difficult without burning fuel
  - Carbon capture and storage is a potential solution here

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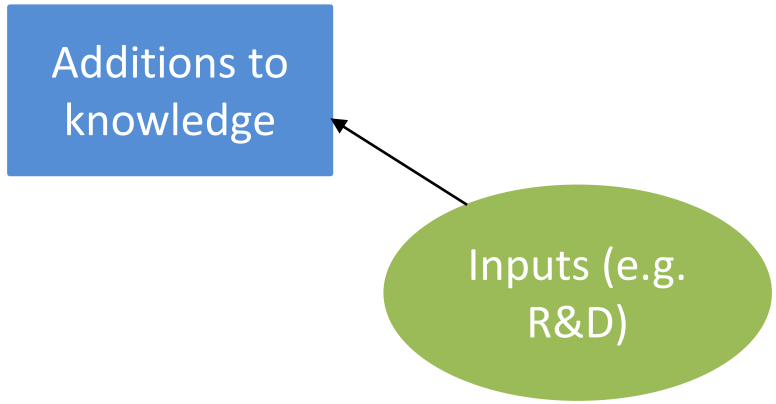
Measuring Environmental Technical Change

- The knowledge that makes any technology valuable improvement is an abstract concept

Additions to knowledge

Measuring Environmental Technical Change

- The knowledge that makes any technology valuable improvement is an abstract concept
  - We observe either inputs that create knowledge or outputs that contain knowledge



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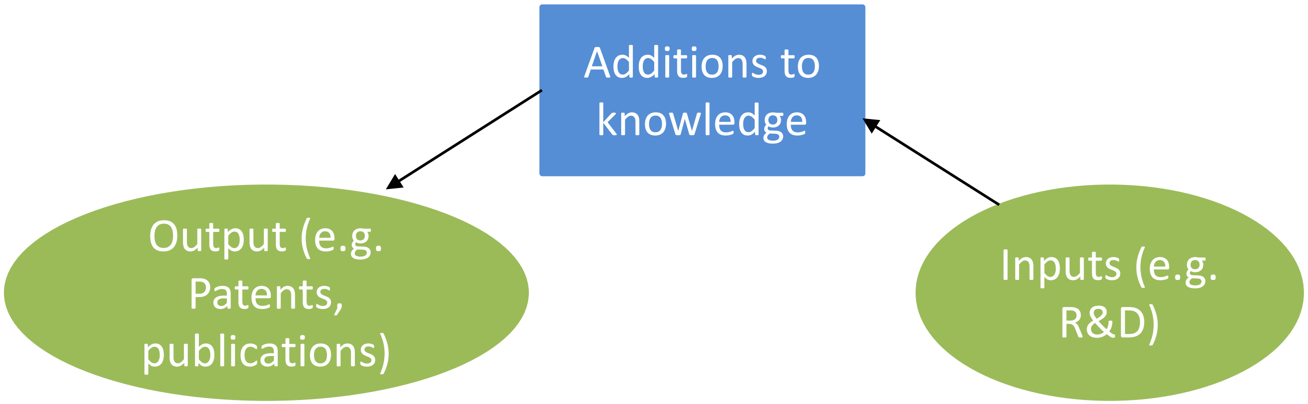

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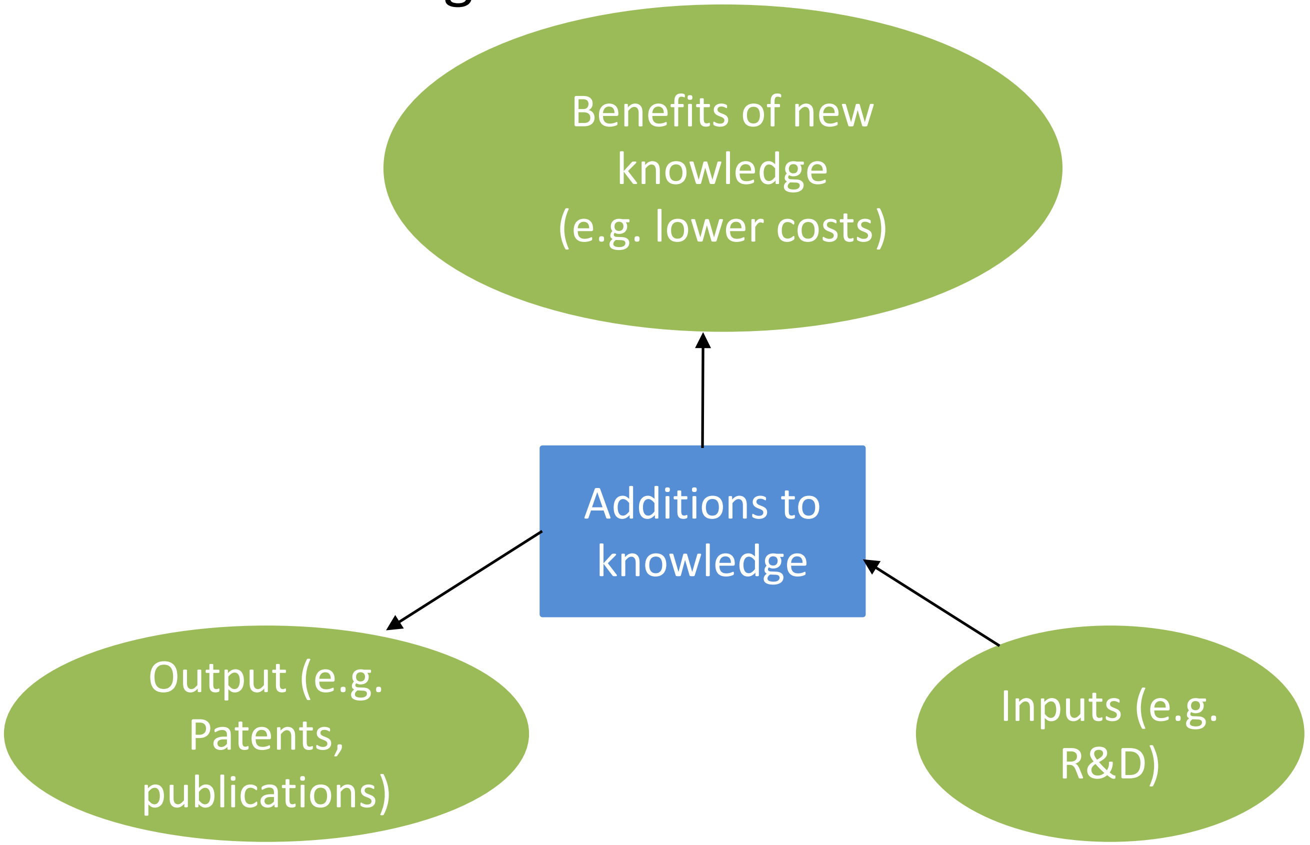

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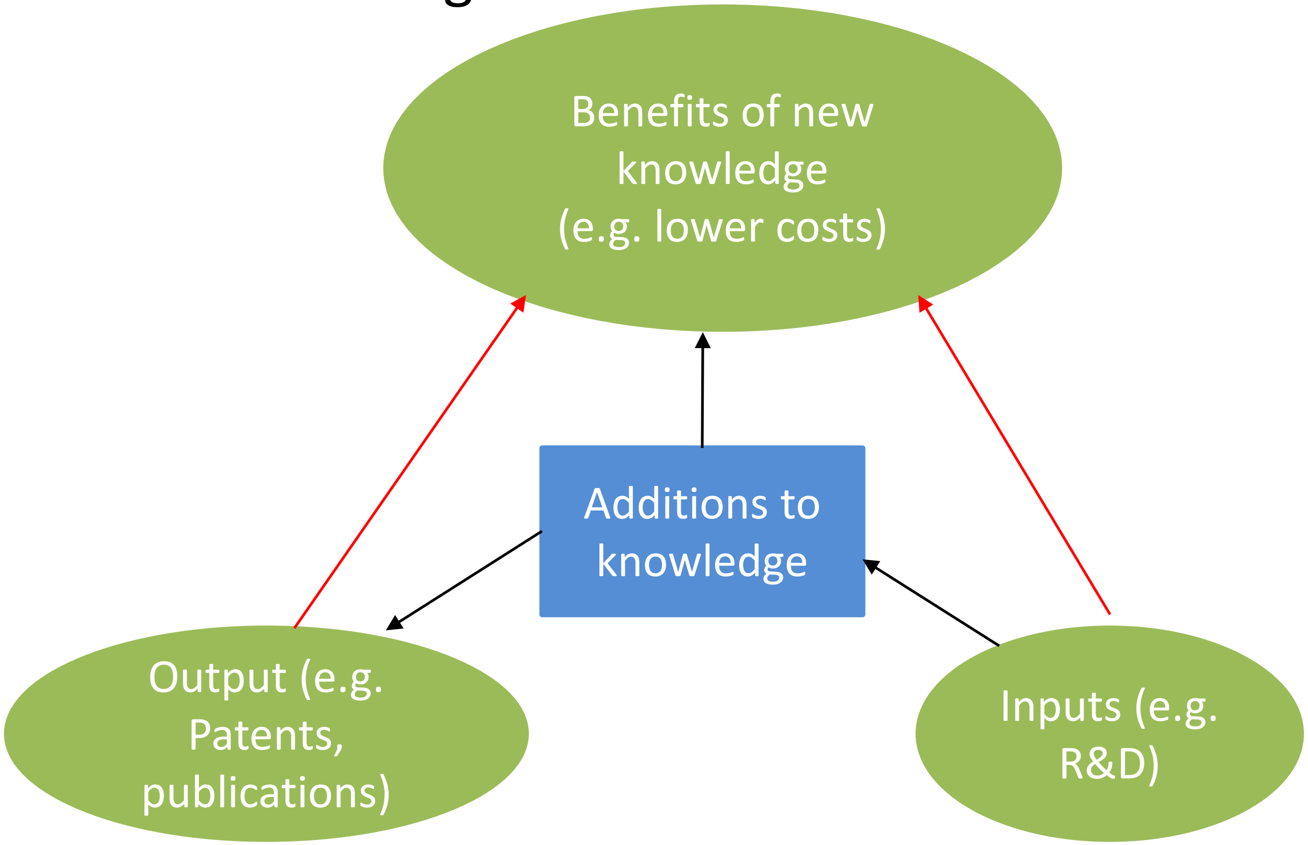

Measuring Environmental Technical Change

- The knowledge that makes any technology valuable is an abstract concept
  - We observe either inputs that create knowledge or outputs that contain knowledge
- Common data sources:
  - R&D expenditures
  - Patents
  - Surveys

Measuring Environmental Technical Change

- R&D expenditures
  - Measure inputs into the innovation process
  - However, detailed innovation on green R&D is often unavailable
  - Most widely used R&D are public R&D expenditures on energy R&D (source: International Energy Agency)
    - Even this can be noisy. For example, one country may include basic R&D on semiconductors as investment in photovoltaic research while another may not (Gallagher *et al*. 2011)

Measuring Environmental Technical Change

- Patents
  - Measure outputs of the innovation process
    - However, often used as a proxy for innovative activity (e.g. Griliches 1990)
  - Provide a more detailed record of innovation

(12) **United States Patent**
Wilkins et al.

(10) **Patent No.: US 6,924,565 B2**
(45) **Date of Patent: Aug. 2, 2005**

(54) **CONTINUOUS REACTIVE POWER SUPPORT FOR WIND TURBINE GENERATORS**

(75) Inventors: **Thomas A. Wilkins**, Tehachapi, CA (US); **Nagwa M. Elkachouty**, Tehachapi, CA (US); **Reigh A. Walling**, Clifton Park, NY (US); **James P. Lyons**, Niskayuna, NY (US); **Robert W. Delmerico**, Clifton Park, NY (US); **Sumit Bose**, Niskayuna, NY (US); **Nicholas Wright Miller**, Delmar, NY (US)

(73) Assignee: **General Electric Company**, Schenectady, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 123 days.

(21) Appl. No.: **10/643,297**

(22) Filed: **Aug. 18, 2003**

(65) **Prior Publication Data**

US 2005/0040655 A1 Feb. 24, 2005

(Under 37 CFR 1.47)

(51) **Int. Cl.**[7] **F02D 9/00**
(52) **U.S. Cl.** **290/44**; 290/55; 322/29
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Primary Examiner—Nicholas Ponomarenko
(74) *Attorney, Agent, or Firm*—Blakely, Sokoloff, Taylor & Zafman LLP

(57) **ABSTRACT**

Real and reactive power control for wind turbine generator systems. The technique described herein provides the potential to utilize the total capacity of a wind turbine generator system (e.g., a wind farm) to provide dynamic VAR (reactive power support). The VAR support provided by individual wind turbine generators in a system can be dynamically varied to suit application parameters.

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Measuring Environmental Technical Change

- Patents
  - Measure outputs of the innovation process
    - However, often used as a proxy for innovative activity (e.g. Griliches 1990)
  - Provide a more detailed record of innovation
    - Patent classifications detail technology types
    - Country of inventor & where patent protection sought
  - Cautions:
    - Variations in patent law must be considered
    - Quality of patents varied
    - Need to be able to clearly identify patents
      - More likely to patent products than new processes (Levin *et al.*1987)

Measuring Environmental Technical Change

- Surveys
  - A popular source is the Community Innovation Survey (CIS)
    - CIS is a bi-annual survey of innovative European firms
    - Beginning in 2008, the CIS survey has included a block of questions on eco-innovation
  - Surveys allow for more nuanced observation of eco-innovation
    - Environmental benefits do not need to be the primary goal of a new product or process. The definition of eco-innovation used in the survey focuses on results.
      - Thus, eco-innovations could be the unexpected result of other innovative activity (Hornbach et al. *EcolEcon*, 2012).
    - Particularly useful to identify process innovations (Frondel *et al*. *Bus. Strategy & Envi*, 2007)
      - Find end-of-pipe solutions more often used to comply with regs
      - Process innovations tend to be market driven (e.g. cost savings)

Measuring Environmental Technical Change

- What are the effects of innovation?
  - Newell *et al*. (*QJE*, 1999) demonstrate a correlation between energy prices and the energy efficiency of home appliances available for sale between 1958 and 1993
  - Knittel (*AER*, 2011) uses the relationship between fuel efficiency and vehicle characteristics to infer technological progress
    - Finds fuel economy standards had a positive effect on observed technological progress for cars, but not for trucks

Measuring Environmental Technical Change

- Learning Curves
  - Learning-by-doing occurs when the costs to manufacturers or users fall as cumulative output increases (Arrow, 1962, Rosenberg, 1982).
  - Commonly is measured in the form of “learning” or “experience” curves: how much unit costs decline as a function of experience or production

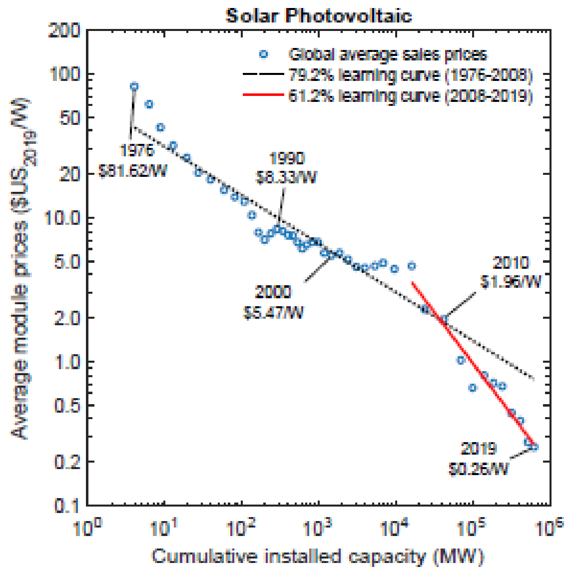

Figure 2: Price dynamics of solar PV modules.

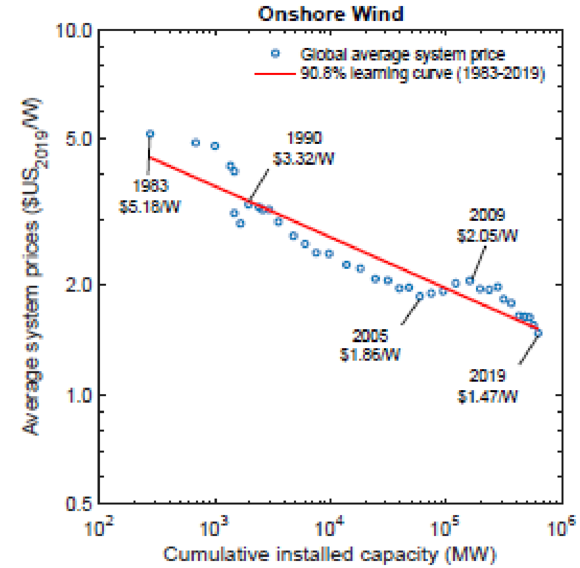

Figure 4: Price dynamics of onshore wind turbines.

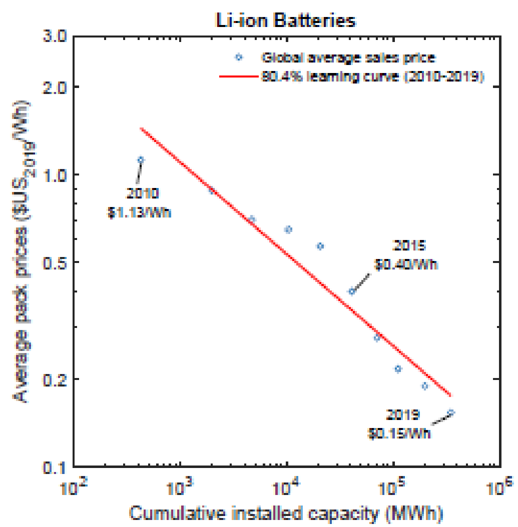

Figure 5: Price dynamics of Li-ion battery packs.

Source: Glenk *et al.* (2021) "Cost Dynamics of Clean Energy Technologies" ZEW Discussion Paper 21-054.

Measuring Environmental Technical Change

- Learning curves provide useful information on changing costs, but simple learning curves do not establish causation between experience and costs
  - Two-factor learning curves combine data on experience and R&D (e.g.Klaasen *et al.*, 2005; Söderholm and Sundqvist, 2007; Söderholm and Klaasen, 2007; Ek and Söderholm, 2010)
    - Typically aggregate R&D into a knowledge stock
    - Söderholm and Sundqvist address potential endogeneity between investments in capacity and R&D
      - Estimate LBD rates around 5 percent, and LBS rates around 15 percent, suggesting that R&D, rather than learning-by-doing, contributes more to cost reductions
      - However, results are very sensitive to the model specification, illustrating the difficulty of sorting through the various channels through which costs may fall over time
    - Data limitation: these models only includes public R&D – what is truly identified?

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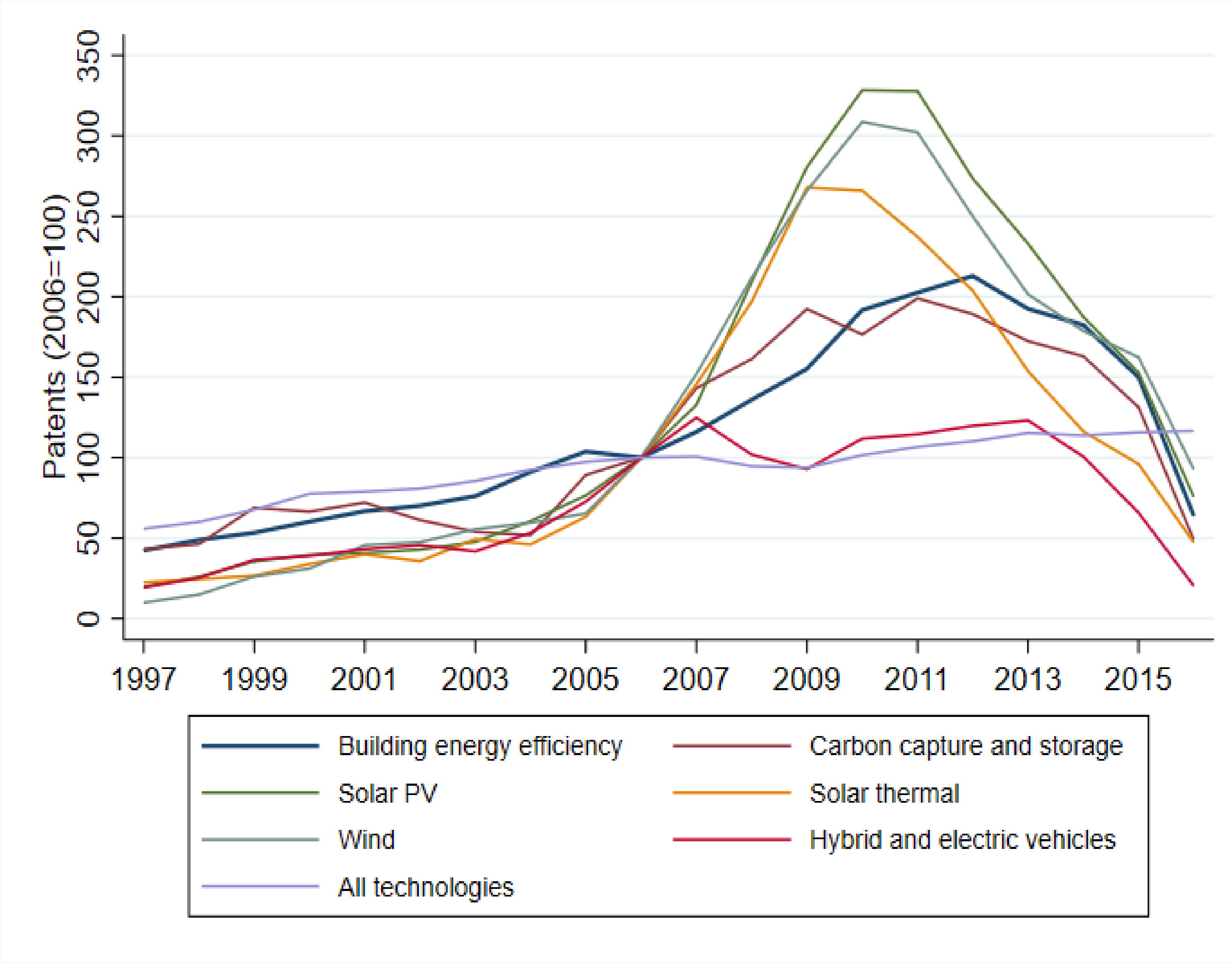
Clean Energy Innovation Trends

- Recent patent trends show progress made and suggest areas in need of continued innovation

Global Energy Patents: Clean Energy

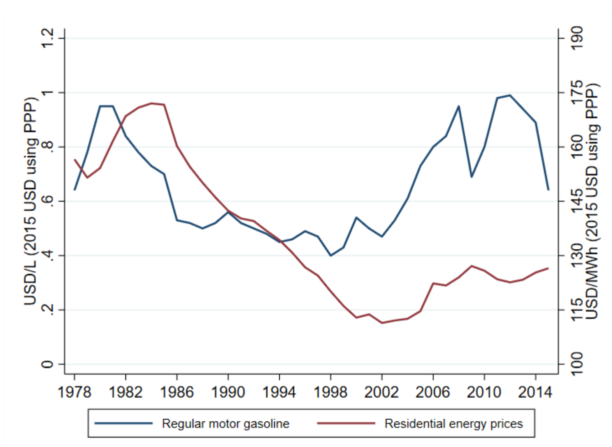


Source: Popp *et al*. (*NBER WP*#27145, 2020)

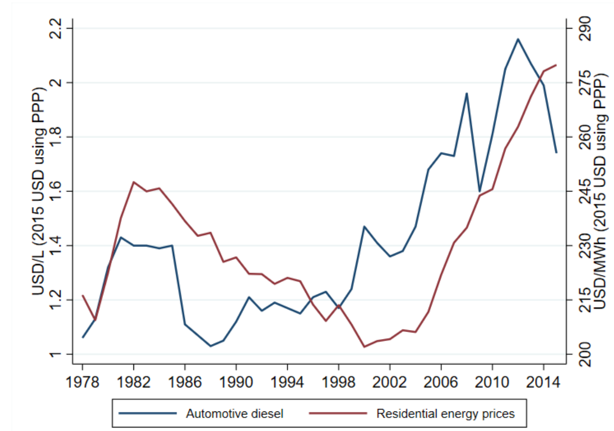
Clean Energy Innovation Trends

- Why has energy innovation fallen? Possible explanations include (Popp *et al., NBER WP*#27145, 2020):
  - The role of prices
    - Both the recent increase and decrease in patenting coincide with trends in energy prices, particularly in the fuel sector

A: United States



B. European Union



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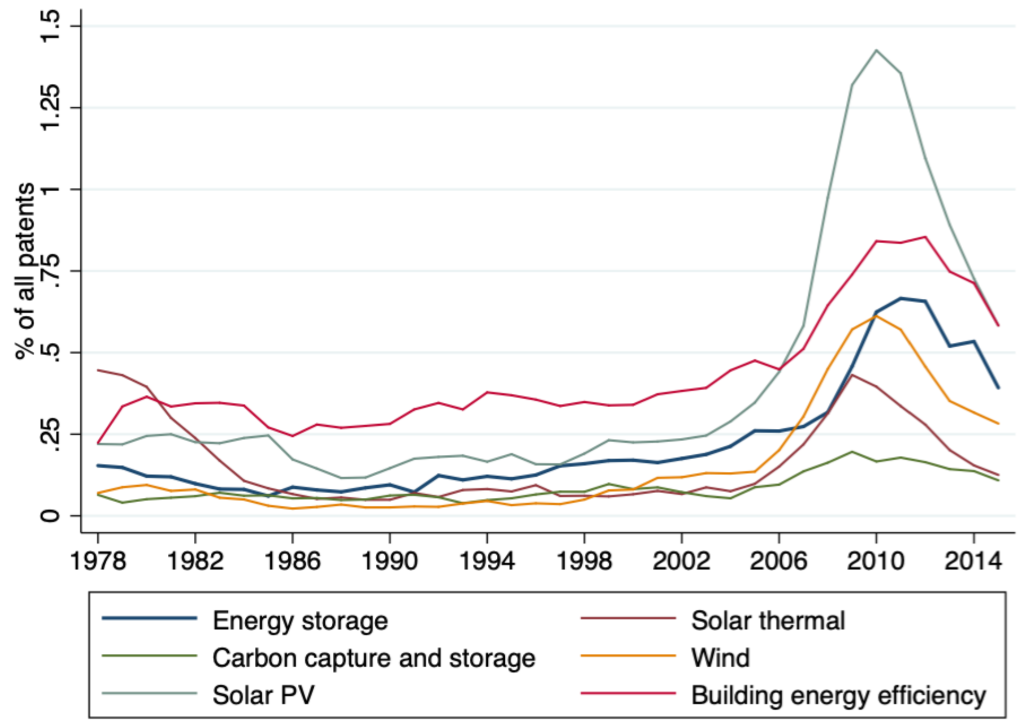
    - Both the recent increase and decrease in patenting coincide with trends in energy prices, particularly in the fuel sector
    - But growth in patenting in late 2000s is unprecedented => other policies must also matter



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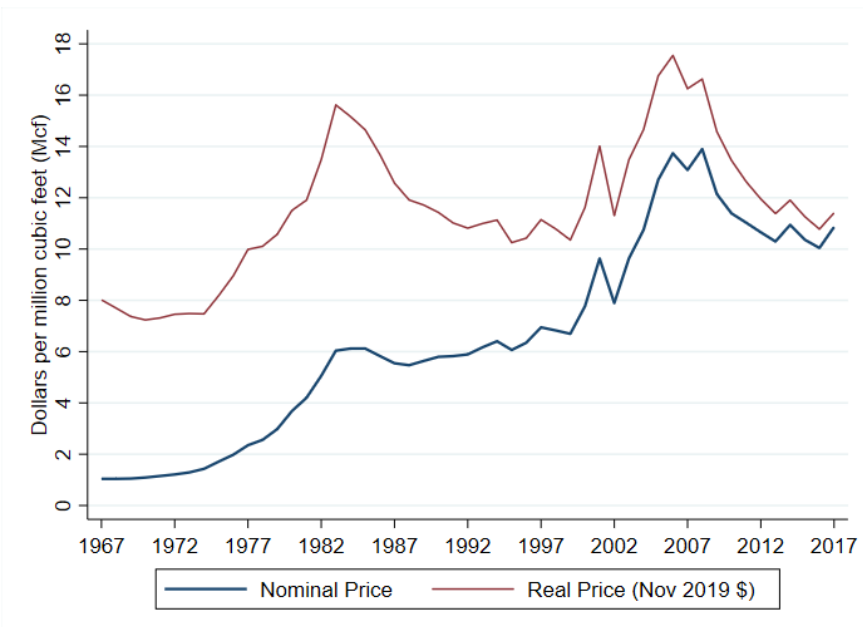
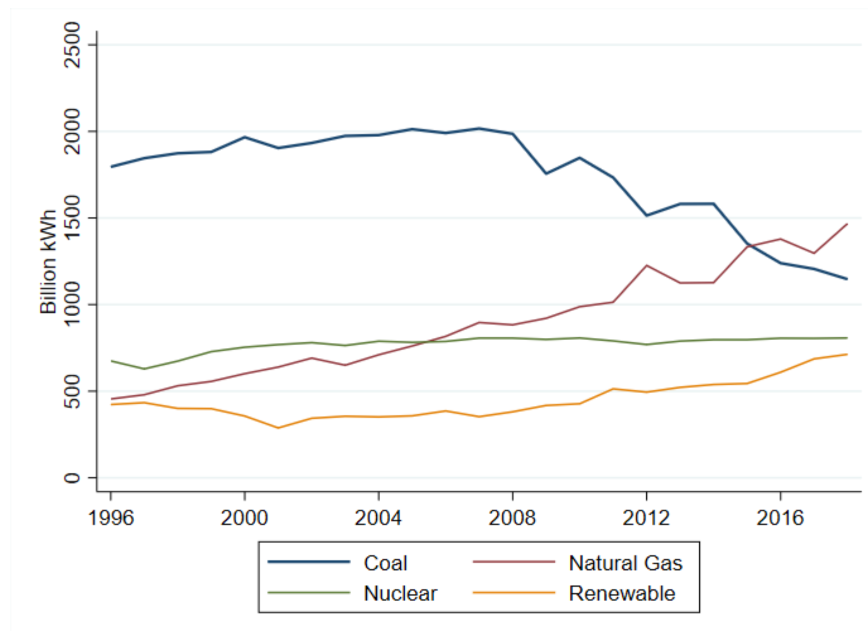
Clean Energy Innovation Trends

- Why has energy innovation fallen? Possible explanations include (Popp *et al., NBER WP*#27145, 2020):
  - The role of prices
  - The role of "fracking" (Acemoglu *et al*. WP 2019)
    - Fracking led to lower natural gas prices and increased electricity generation from natural gas in the US

Annual Residential Natural Gas Price



U.S. Electricity Generation by Fuel Source



Clean Energy Innovation Trends

- Why has energy innovation fallen? Possible explanations include (Popp *et al., NBER WP*#27145, 2020):
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  - The role of "fracking" (Acemoglu *et al*. WP 2019)
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  - Diminishing returns to research
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    - Given how quickly clean energy patenting increased in the early 2010s, might promising avenues of research simply dried up?

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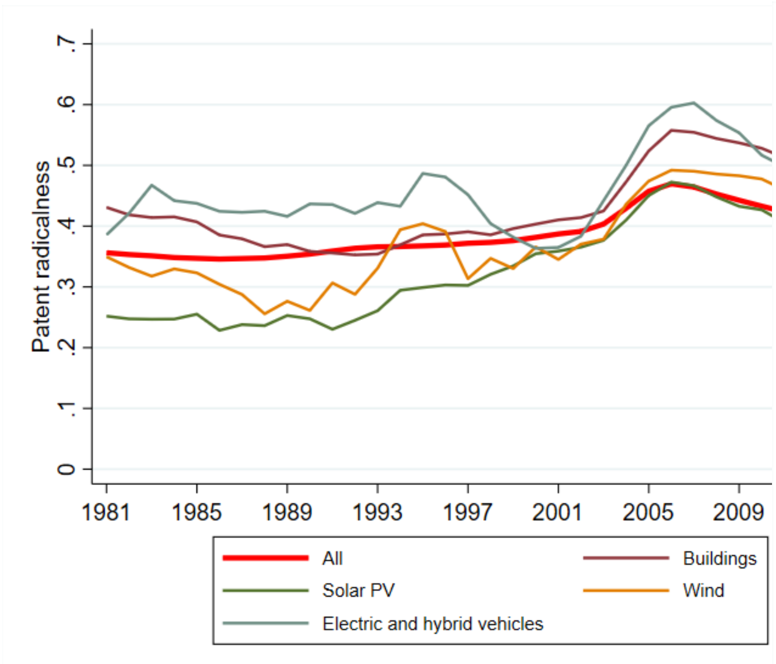
    - Given how quickly clean energy patenting increased in the early 2010s, might promising avenues of research simply dried up?
    - Two measures:
      - Radicalness: To what extent do patents build upon ideas outside the patented technological domain?
      - Originality: What is the breadth of technology on which a patent relies

Clean Energy Innovation Trends

Radicalness: *Clean Energy Technologies*



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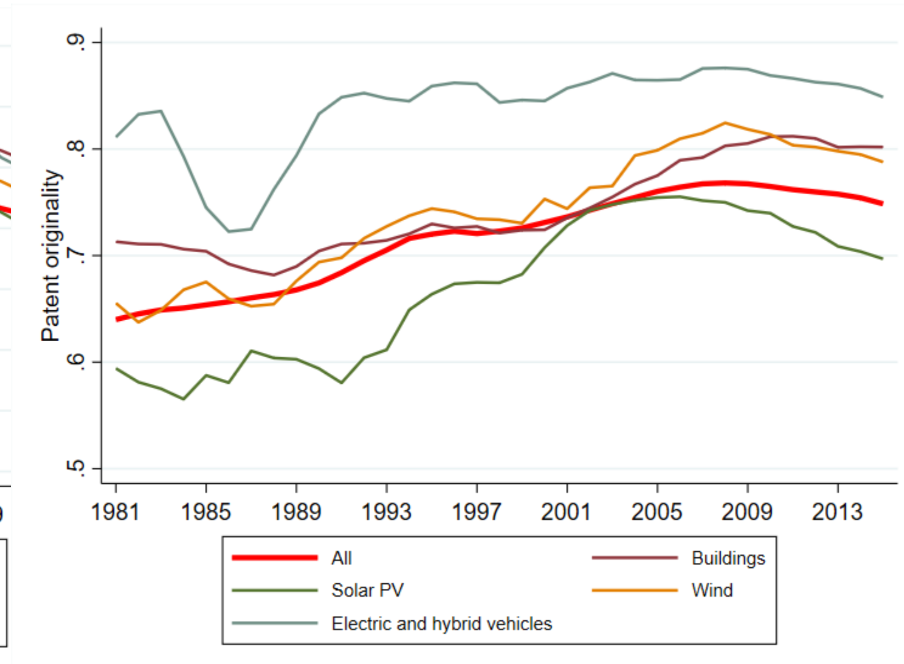

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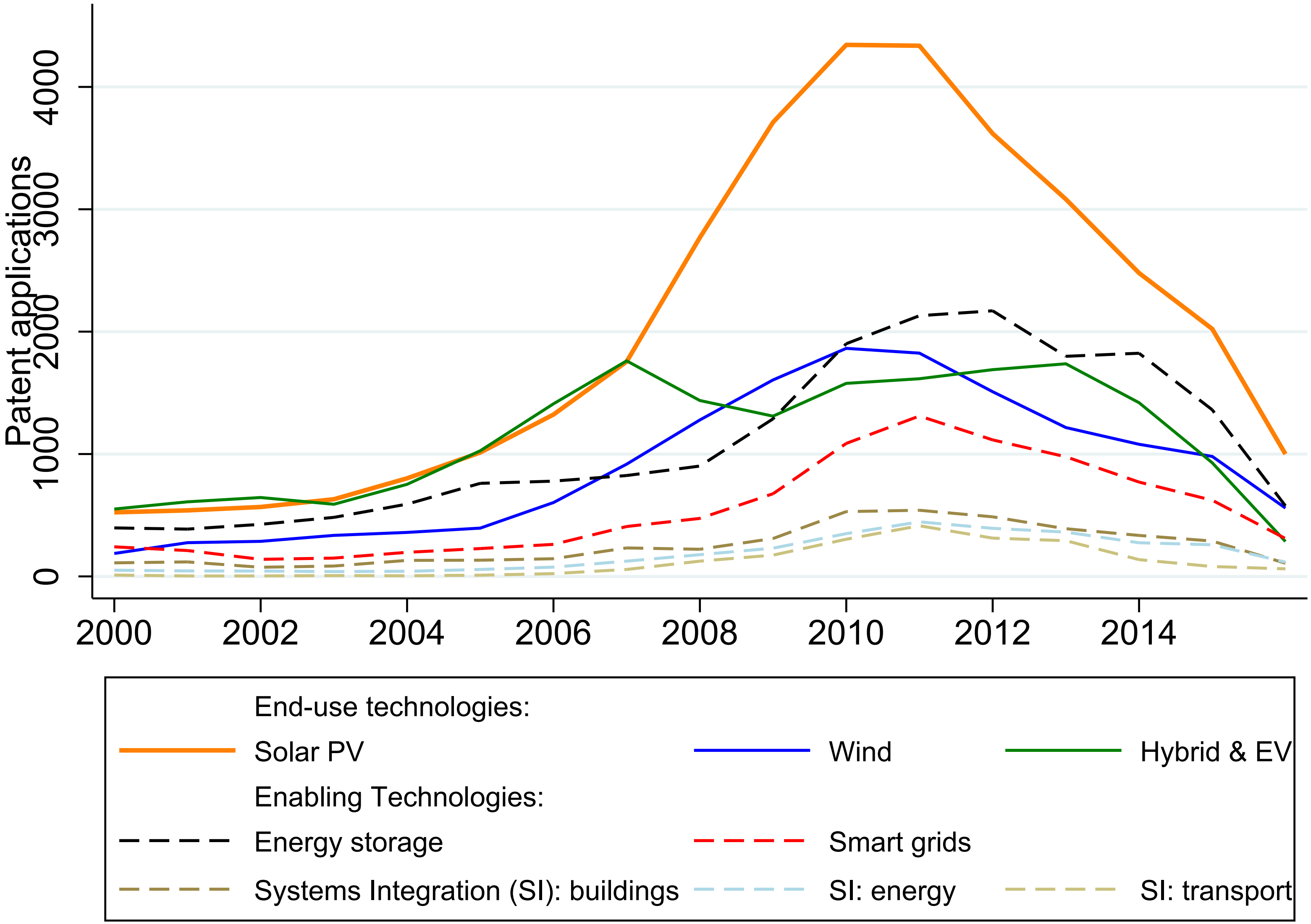
  - Diminishing returns to research
  - Innovation worked
    - Related to diminishing returns
    - By 2017 solar PV costs had fallen below what experts had earlier predicted for the year 2030 (Nemet, 2019)
    - But…

Global Energy Patents: Enabling Technologies



Source: based on data from Popp *et al*. (*NBER WP#*27145, 2020)

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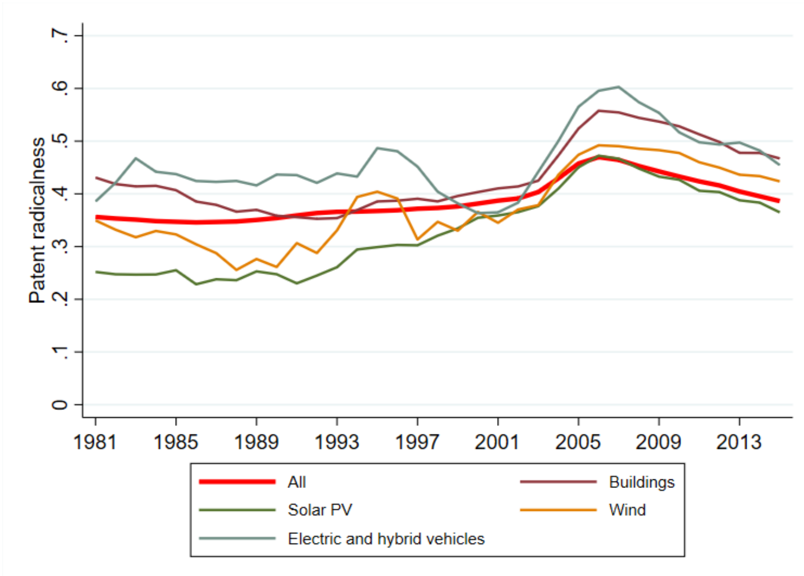

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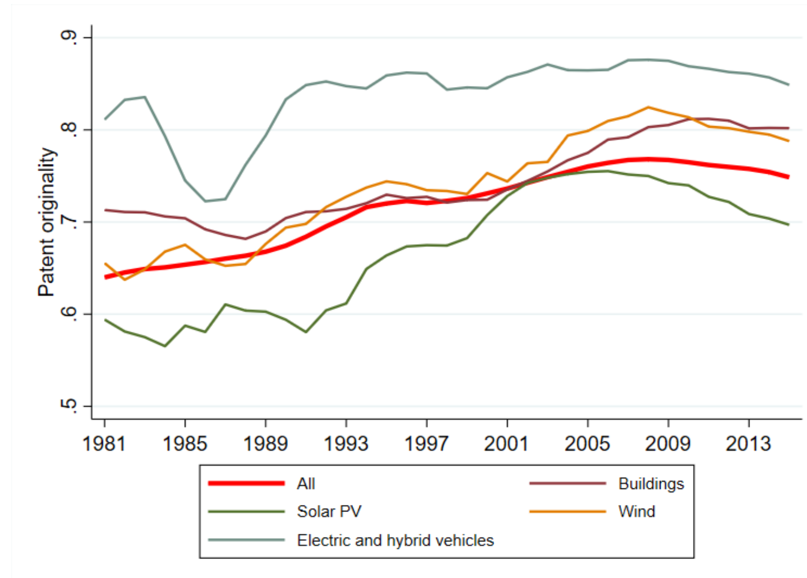

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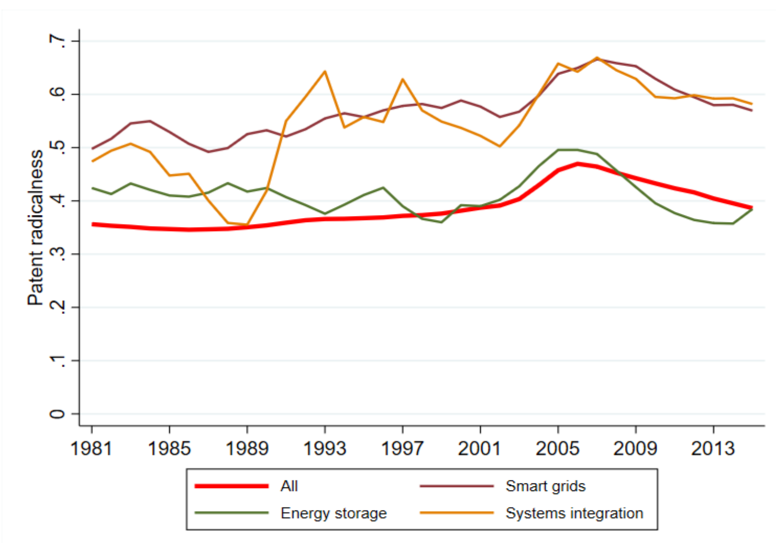

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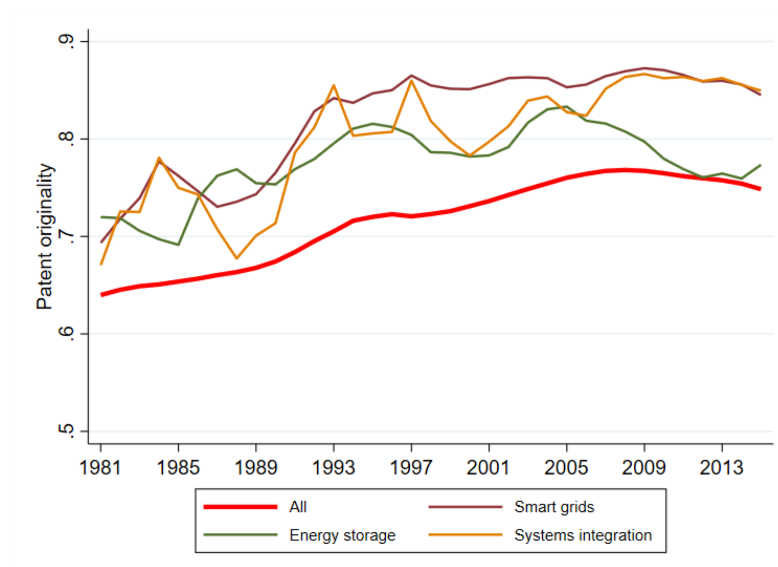

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- These enabling technologies need more government support

1. Challenges to a Renewable Energy Transition
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4. Technological Change & the Environment: Theory
5. The Role of Policy: Broad-based Policies
6. Targeted Policies: Which Policy Tools to Use?
7. Public Energy R&D

Technological Change & the Environment

- Technological change proceeds in three stages:
  - *Invention:* an idea must be born
  - *Innovation:* new ideas are then developed into commercially viable products
    - Often, these two stages of technological change are lumped together under the rubric of research and development (R&D)
  - *Diffusion:* to have an effect on the economy, individuals must choose to make use of the innovation

Technological Change & the Environment

- Clean energy innovation suffers from two market failures
  - *Environmental Externalities*
    - Pollution created in the production or use of a product are not normally included in the price of the product
      - Thus, neither firms nor consumers have incentive to reduce pollution on their own
    - This limits the market for technologies that reduce emissions, which in turn reduces the incentives to develop such technologies
    - Addressed by environmental policy (a/k/a *demand-pull* policies)

Technological Change & the Environment

- Clean energy innovation suffers from two market failures
  - *Environmental Externalities*: social benefits of clean energy associated with pollution reductions are not reflected in market prices without government intervention
    - Addressed by environmental policy (a/k/a *demand-pull* policies)
  - *Knowledge as a Public Good*: innovation leads to knowledge spillovers—additional innovations, or even to copies of the current innovations, that benefit the public as a whole, but not the original innovator
    - Addressed by science and technology policy (a/k/a *technology-push* policies)
      - May be general (IP) or specific (subsidies for renewable R&D)

Technological Change & the Environment

- These two externalities could, in principle, be addressed separately
  - Use science policy to address knowledge market failures in *all* sectors of the economy
  - Use carbon pricing to "get the prices right"

- While science policy plays a role, it is not a substitute for environmental policy
  - Science policy can help lower the costs of environmental policies
  - Science policy can help with the *development* of technologies, but not with the *diffusion* of technologies

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The Role of Policy: Broad-based Policies

- Environmental policy creates incentives for private sector innovation
  - Cleaner technologies often have higher costs
  - Users care about services provided by energy, not how it is produced
    - That is, innovation affects the generation of electricity, but not the end product provided to the user
    - Compare to life sciences and ICT, where innovation affects the product itself

    => Product differentiation difficult for clean energy!

The Role of Policy: Broad-based Policies

- Economists tend to prefer market-based regulation over command-and-control options
  - Minimize compliance costs
  - Provide greater incentives for innovation
    - Command-and-control regulation provides incentives to meet, but not exceed, standards (Popp, *JPAM*, 2003)
    - In contrast, market-based options provide rewards for continual improvement

The Role of Policy: Broad-based Policies

- However, policy distinctions can be subtler:

  Technology neutral

  - Carbon tax
  - Cap-and-trade
  - Renewable Energy Certificates/Renewable Portfolio Standards

  Technology-specific

  - Feed-in tariffs
  - Renewable auctions
  - Investment subsidies
  - Technology mandates

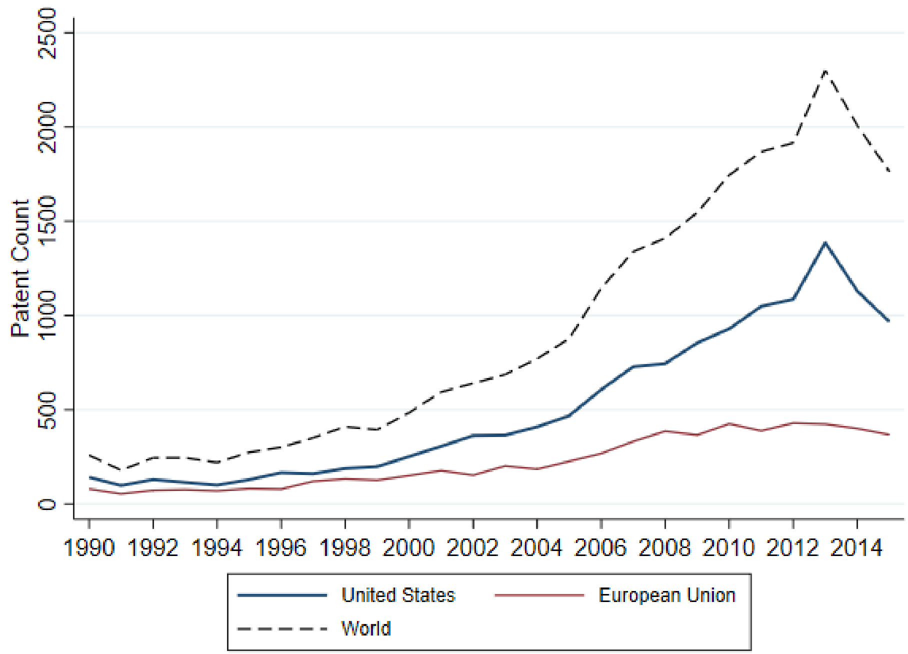
The Role of Policy: Broad-based Policies

- Evidence on broad-based polices & prices
  1. Higher energy prices encourage innovation
     - Newell *et al*. (*QJE* 1999) & Popp (*AER* 2002) both find most of the response of R&D to higher energy prices occurs within 5 years
     - Magnitude of effect:
       - 10% increase in energy prices => about a 3.5% in alternative energy and energy efficiency patents (Popp *AER* 2002, Verdolini and Galeotti, *JEEM* 2011)
       - Aghion *et al.* (*JPE* 2016): 10% higher fuel price =>
         - » 10% percent more EV & hybrid patents,
         - » 4-6% more “clean & gray” patents,
         - » 7% *fewer* fossil-fuel patents (Aghion *et al.*, *JPE* 2016)

The Role of Policy: Broad-based Policies

- Evidence on broad-based polices & prices
  1. Higher energy prices encourage innovation
     - Policies directly addressing emissions matter, as higher energy prices also encourage the search for more fossil fuels

Hydrofracturing patents, 1990-2015



Source: Popp *et al*. (*NBER WP*#27145, 2020)

David Popp

Maxwell | Syracuse University

The Role of Policy: Broad-based Policies

- Evidence on broad-based polices & prices
  1. Higher energy prices encourage innovation
  2. Prices alone do not encourage energy efficient innovation
     - The resulting reduced emissions are an external benefit
     - Therefore, individuals underinvest in energy efficient technologies
     - In these cases, energy efficiency regulations help
       – Knittel (*AER* 2011): that fuel economy regulations have a positive effect on observed technological progress for cars, but not for trucks
       – Noailly (*Energy Econ* 2012): energy prices are less effective for promoting innovation on home energy efficiency
         » Prices are particularly ineffective less-visible technologies such as insulation (e.g. installed by builders)
         » Building code changes lead to more innovation than energy prices here

The Role of Policy: Broad-based Policies

- Evidence on broad-based polices & prices
  1. Higher energy prices encourage innovation
  2. Prices alone do not encourage energy efficient innovation
  3. Even technology-neutral policies implicitly favor some technologies over others
     - Policies that let the market "pick winners" will focus research efforts on technologies closest to market (Johnstone *et al*. *ERE* 2010)
       - Renewable energy mandates => wind innovation
       - Guaranteed prices (e.g. feed-in tariffs) => solar innovation
         - » Consider, for example, solar energy in Germany
     - Suggests a trade-off, as policies promoting specific technologies may increase short-run compliance costs

The Role of Policy: Broad-based Policies

- Solutions?
  - Combine broad-based policies with subsidies for technologies furthest from market
    - Most effective if target other market failures (Fischer *et al*. *JAERE* 2017, Lehmann & Söderholm *ERE* 2018)
  - Use government R&D to support long-term research needs (Acemoglu et al., *JPE* 2016)

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Which policy tools to use?

- The presence of other market failures inform policy choice
  - Capital market failures
    - Energy innovations take longer to get to market (Popp, *Res. Policy*, 2017)
    - Often have large fixed costs
    - Government support helps overcome funding hurdles
    - Policy examples:
      - DOE Loan Guarantee Program
      - US Dept. of Energy SBIR grants
        - » Recipients 2X as likely to receive subsequent venture capital, produce more patents, & earn more revenue (Howell, *AER* 2017)

Which policy tools to use?

- The presence of other market failures inform policy choice
  - Capital market failures
  - Path dependency
    - Developing charging infrastructure is necessary before consumers will purchase electric vehicles
    - The private sector won't develop charging infrastructure until there are enough electric vehicles on the road to make investment profitable

      => early adopters of electric vehicles provide external benefits through network effects, justifying subsidies
    - Few empirical papers study path dependency explicitly
      - Aghion *et al.* (*JPE* 2016), Stucki and Woerter (*Energy Journal* 2017): a firm's previous patenting affects the direction of current research
    - Path dependency creates a market failure if switching costs make it difficult for firms previously investing in one type of technology to switch to profitable opportunities in another (Lehmann & Söderholm *ERE* 2018)
      - Empirical work on this still needed

Which policy tools to use?

- The presence of other market failures inform policy choice
  - Capital market failures
  - Path dependency
  - Learning-by-doing
    - Experiences of early entrants provide lessons for future technology development
    - Justifies additional deployment policies (e.g. tax credits)
    - But LBD effects are small
      - Nemet (*JPAM* 2012): Studies wind in California
        - » Finds evidence of both internal and external learning
        - » However, learning is subject to diminishing returns and decays quickly
      - Tang (*Energy Policy* 2018) considers learning from wind turbine producers and operators
        - » Wind farm operation improves with experience
          - Improvements are greater if the wind farm developer collaborates with the same turbine manufacturer
          - Gains can be partially internalized
      - Fischer *et al*. (*JAERE*, 2017): R&D market failures more important than LBD, so targeted deployment subsidies should be limited

Which policy tools to use?

- The presence of other market failures inform policy choice
  - Capital market failures
  - Path dependency
  - Learning-by-doing
  - Knowledge spillovers: are they different for energy?
    - Clean patents generate larger knowledge spillovers than the dirty technologies they replace (Dechezleprêtre et al., working paper 2017)
    - Justifies increased government funding for clean energy R&D

Which policy tools to use?

- Spillovers may also occur across borders
- Will policy induce innovation at home or abroad?
  - Most existing work on energy innovation looks at national-level policies
- A few studies consider both foreign and domestic policies
  - Peters *et al*. (*Research Policy* 2012): Both domestic and foreign demand-pull policies are important for the development of solar PV technology
  - Dechezleprêtre and Glachant (*ERE* 2014): Both promote innovation activity in wind
    - Marginal effect of policies implemented at home to be 12 times higher
    - But foreign market size is larger, so overall impact greater
  - Fabrizio *et al*. (*Research Policy* 2017): Studies energy storage innovation
    - *Demand-pull* policies promote both domestic innovation and increase technology transfer
    - *Technology-push* policies promote domestic innovation. Do not increase technology transfer.

Which policy tools to use?

- Spillovers may also occur across borders

- Who captures the benefits of innovation?
  - Verdolini and Galeotti (*JEEM* 2011): foreign knowledge increases domestic patenting
    - A 10% increase in domestic knowledge increases patenting by 3%, and a 10% increase in foreign knowledge increases patenting by 9.6%
  - Gerarden (2018) analyzes the effect of consumer subsidies for solar panels
    - By permanently reducing future costs, the benefits of induced innovation may extend beyond the life of a subsidy
    - Accounting for induced innovation increases the benefits of German PV subsidies by at least 22%
      - However, most of those benefits are generated by future solar panel adoption that occurs outside Germany
      - Thus, while first-order benefits such as reduced emissions may be enough to justify promoting clean energy policies, the second-order benefits of induced technological change may be of less concern to local policy makers

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- Coordination among states may improve effectiveness
  - EU efforts to reduce fragmentation of clean energy research increased rates of patent citations among EU researchers from different countries (Conti *et al.*, *Research Policy* 2018)

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The Role of Energy R&D

- Targeted subsidies focus on deployment. They induce innovation by creating new markets for renewable energy.

- These policies do not address market failures affecting the supply of innovation

- Government investments in energy R&D address the supply-side

Energy R&D: Empirical Studies

- Effect of public R&D on new energy patents
  - Popp (*AER* 2002) uses a distributed lag framework
    - US government energy R&D served as a substitute for private energy R&D during the 1970s, but as a complement to private energy R&D afterwards
    - Even afterwards, however, effect of public R&D smaller than energy prices
  - Many recent studies use just a single year of lagged public R&D (e.g. Johnstone *et al* 2010, Verdolini and Gaelotti 2011, Dechezleprêtre and Glachant 2014, Nesta *et al*. 2014)
    - Most (but not all) find a positive relationship between public R&D and patents
    - But, endogeneity is a concern

- Howell (*AER* 2017) looks at US DOE SBIR grants using a regression discontinuity design. Grant recipients are:
  - 2X as likely to receive subsequent venture capital
  - Produce more patents
  - Earn more revenue

Energy R&D: Empirical Studies

- Most evaluations of energy innovation use patent data
- 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
  - Both use citations to track flows of knowledge over time and across institutions

(12) **United States Patent**
Wilkins et al.

(10) **Patent No.: US 6,924,565 B2**
(45) **Date of Patent: Aug. 2, 2005**

(54) **CONTINUOUS REACTIVE POWER SUPPORT FOR WIND TURBINE GENERATORS**

(75) Inventors: **Thomas A. Wilkins**, Tehachapi, CA (US); **Nagwa M. Elkachouty**, Tehachapi, CA (US); **Reigh A. Walling**, Clifton Park, NY (US); **James P. Lyons**, Niskayuna, NY (US); **Robert W. Delmerico**, Clifton Park, NY (US); **Sumit Bose**, Niskayuna, NY (US); **Nicholas Wright Miller**, Delmar, NY (US)

(73) Assignee: **General Electric Company**, Schenectady, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 123 days.

(21) Appl. No.: **10/643,297**

(22) Filed: **Aug. 18, 2003**

(65) **Prior Publication Data**

US 2005/0040655 A1 Feb. 24, 2005

(Under 37 CFR 1.47)

(51) **Int. Cl.**[7] **F02D 9/00**
(52) **U.S. Cl.** **290/44**; 290/55; 322/29
(58) **Field of Search** .... 290/1 A, 44, 55; 322/27, 28, 29

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Primary Examiner—Nicholas Ponomarenko
(74) *Attorney, Agent, or Firm*—Blakely, Sokoloff, Taylor & Zafman LLP

(57) **ABSTRACT**

Real and reactive power control for wind turbine generator systems. The technique described herein provides the potential to utilize the total capacity of a wind turbine generator system (e.g., a wind farm) to provide dynamic VAR (reactive power support). The VAR support provided by individual wind turbine generators in a system can be dynamically varied to suit application parameters.

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Energy R&D: Empirical Studies

- Links between R&D spending and research outcomes (Popp *Nature Energy* 2016)
  - 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

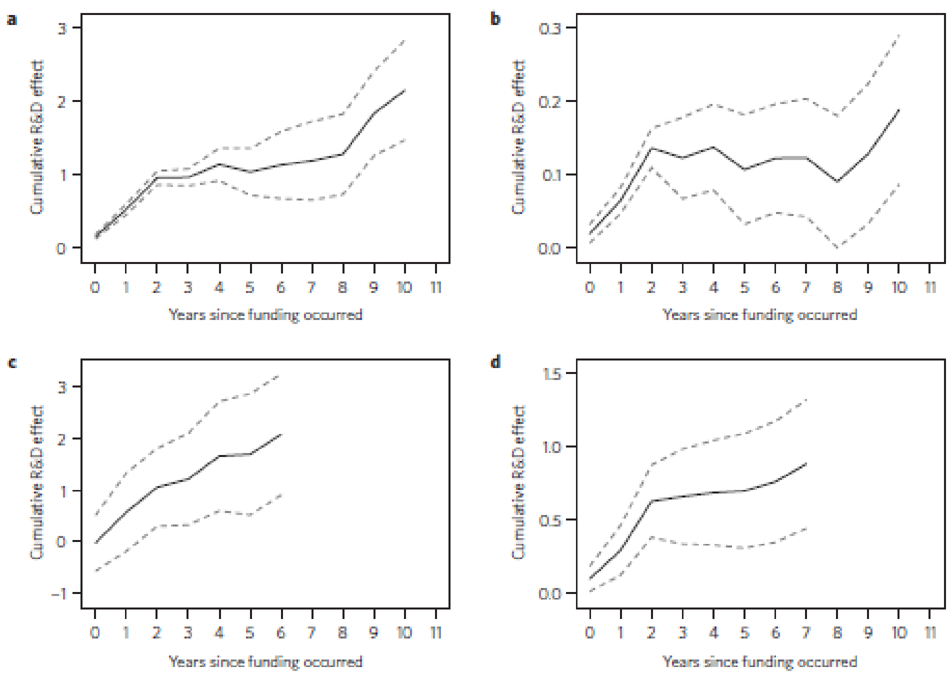

Figure 2 | Cumulative effect of energy R&D on publications. The cumulative effect of an additional US$1 million of public energy R&D on publications through year $t + x$, where x represents years since funding occurred, shown on the x-axis. Dashed lines represent 95% confidence intervals. Biofuels (**a**)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

Energy R&D: Empirical Studies

- Links between R&D spending and research outcomes (Popp *Nature Energy* 2016)
  - 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

Energy R&D: Empirical Studies

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  - 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
  - Linking publications to patents
    - Probability of citation resulting from new R&D funding peaks 10-12 years after funding

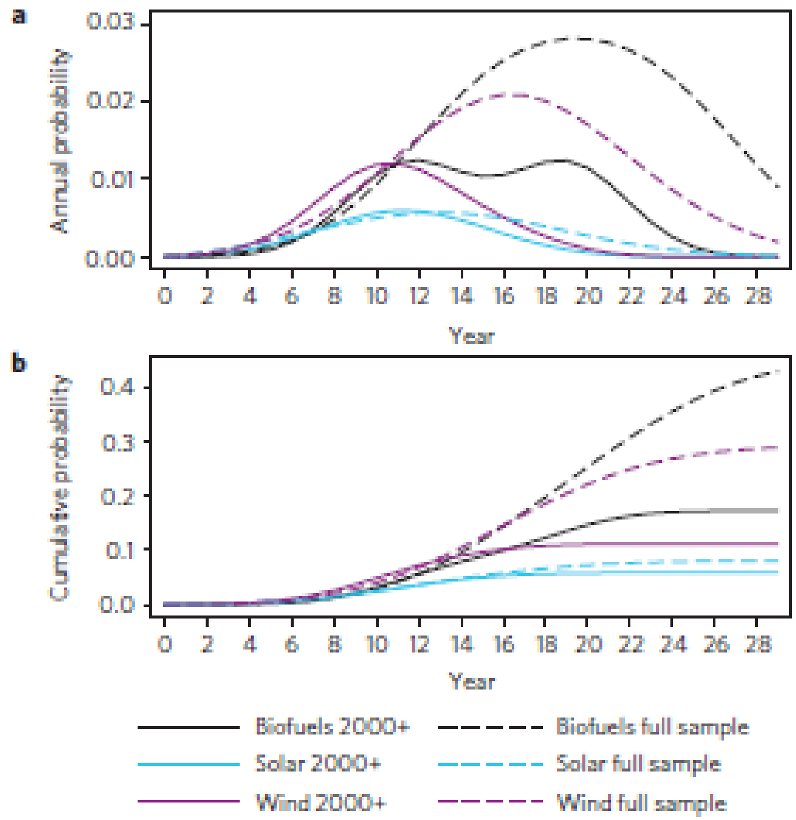

Figure 3 | Increased probability of patent citation from additional energy R&D. a,b, The annual probability of patent citation (**a**) and the cumulative probability of patent citation (**b**) of any article receiving a citation *t* years after an additional US$1 million R&D, from all articles resulting from the increased funding.

Energy R&D: Empirical Studies

- Which institutions provide the most impactful research? Do collaborations matter? (Popp *Research Policy* 2017)
  - Research 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 14% more likely to be cited by other patents
  - Collaborative research enhances the flow of knowledge across institutions
    - Non-company collaboration patents 31% more likely to be cited than university patents
    - Non-company collaborations 60% more likely than university patents to cite other articles
      - Both results excludes self-citations: not just technology transfer within the group

Energy R&D: Guidance for Public Policy

- Determining how much to spend on public energy R&D requires an interdisciplinary approach
  - Engineers are better qualified to determine which projects are most deserving from a technical standpoint
- What economists can provide is guidelines as to how funding should be allocated

Energy R&D: Guidance for Public Policy

- Which technologies to support?
  - To avoid duplicating, and potentially crowding-out, private research efforts, government R&D support should focus on:
    - basic research
    - technologies not yet close to market (e.g. Costantini *et al*. *Research Policy*, 2015 on biofuels)
    - specialized technology with small markets (e.g. industrial energy efficiency)
    - applied research whose benefits are difficult to capture through market activity
      - E.g. improved electricity transmission, energy storage
  - Common theme: high-risk/high-reward projects

Energy R&D: Guidance for Public Policy

- The DOE's Advanced Research Projects Agency-Energy (ARPA-E) is an example of a government agency that has successfully promoted and managed high-risk, high-reward innovation
  – Requires research teams to set clear, measurable goals through various stages of research
  – Gives program directors the ability to terminate or redirect projects not achieving these predetermined milestones
    - Takes the decision to end funding out of the hands of politicians, making it easier to support more high-risk/high-reward projects

Energy R&D: Guidance for Public Policy

- How much to spend?
  - As I find little evidence for diminishing returns, there appears to be room for government energy R&D budgets to expand
    - IEA's proposed doubling of government energy R&D budgets appears feasible
    - But remember that adjustment costs are important
- Patience is important
  - Lags between funding and publication are long
    - 6-10 years for full effect of funding
    - An additional 3-5 years for articles to generate new patent applications
- Evaluating public R&D requires patience from policymakers
  - R&D is uncertain; some projects will fail
- 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

Energy R&D: Guidance for Public Policy

- Finally, remember that R&D is not a substitute for other policies

- Government R&D complements other energy policies
  - In most cases, public R&D doesn't focus on the final product
    - Technology transfer needed to bring results to market
    - Complimentary environmental policies will be important
    - Government R&D will be needed for breakthrough innovations that aren't yet close to market

Energy R&D: Guidance for Public Policy

- What is the appropriate policy mix?
  - Popp (*Climatic Change*, 2006) examines gains from carbon tax & R&D subsidies
    - Only using carbon tax => 95% of welfare gain of both
    - Only using R&D subsidy => 11% of welfare gain of both
  - Fisher & Newell (*JEEM*, 2008) rank emission-reducing policies:
    - (1) emissions price, (2) emissions performance standard, (3) fossil power tax, (4) renewables share requirement, (5) renewables subsidy, (6) R&D subsidy
  - Acemoglu *et al*. (*JPE*, 2016) suggests a larger role for energy R&D subsidies
    - R&D subsidies have the ability to change knowledge stocks
    - If clean technology is far behind, initial R&D subsidies needed to make private R&D on clean technology profitable
      - Dechezleprêtre et al. (2017) find that clean patents generate larger knowledge spillovers than the dirty technologies they replace
      - Suggests high initial R&D subsidies, followed by a gradually increasing carbon tax
  - Fischer *et al*. (*JAERE*, 2017): "Emissions pricing remains the most cost-effective option for reducing emissions"
    - R&D market failures more important than LBD, so targeted deployment subsidies should be limited

Summary

- Targeted policies that address the market failures noted earlier are needed *even if* broad-based carbon pricing becomes a reality

- R&D is not a substitute for energy and environmental policies that create demand for clean energy, but rather complements demand-side policies

- Other targeted policies may build support for future broad-based policies (Meckling *et al*., *Science* 2015)

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Thank You!