How Can Further Innovation Help?

- Possible solutions to the intermittency problem
  - Larger grids easier to balance
  - Demand-response strategies (e.g. "smart grid")
  - Energy storage

How Can Further Innovation Help?

- Energy Storage
  - Because wind and solar are intermittent sources, they cannot fully power the electric grid unless power can be stored
    - While costs are falling, energy storage is still expensive
    - Thus, most renewable sources are not paired with energy storage

How Can Further Innovation Help?

- Energy Storage Techniques
  - Pumped hydro storage
    - Excess power used to pump water to a reservoir
    - Currently lowest cost storage option
    - Example: Denmark and Norway work in tandem to provide power
      - When winds are favorable, Denmark exports wind energy to Norway. When not, Norway exports hydropower to Denmark.
      - Essentially, the hydropower not used when wind energy is exported is "stored" energy
    - Globally, most energy storage today uses pumped hydro, but future expansion will be limited
      - Requires appropriate geography
      - Potential environmental effects of building new dams

How Can Further Innovation Help?

- Energy Storage Techniques
  - Batteries
    - Most often use lithium-ion batteries
      - Short-duration (≈30 minutes, to smooth spikes in power grid)
      - Long-duration (for storing intermittent power for later use)
    - Most commonly used energy storage in US
    - Costs have fallen dramatically since 2010
    - Barriers to battery development:
      - Safety concerns (e.g. overheating)
      - Patchwork of local regulations
      - New materials needed to get costs lower

How Can Further Innovation Help?

- Zero-carbon options for processes that cannot run on electricity
  - Biofuels
    - Currently, this is the largest source of renewable energy
      - However, much of this is low-technology uses in developing countries. Presumably usage of these fuels will fall as countries grow.
      - Other fuels include things such as ethanol
    - Carbon released when burned is same as carbon absorbed as the plant grows
    - But requires energy to produce, so only zero-carbon if produced using zero-carbon energy
      - Corn ethanol in US averages only 39% lower CO2 emissions than the gasoline it replaces
    - Is there enough farmland to grow the needed feedstocks *as well as supplying necessary food supply*?

How Can Further Innovation Help?

- Zero-carbon options for processes that cannot run on electricity
  - Carbon capture and storage (a/k/a carbon sequestration)
    - Carbon is captured and stored underground or used in an industrial process
      - Can be done before combustion (removing carbon from fuel) or afterwards (removing from waste gases)
      - Currently used for enhanced oil recovery
    - Storage space is an issue
      - Oil & gas reservoirs, deep saline aquifers, and un-minable coal beds are options
      - Must be stored in formations with impermeable cap rock to avoid leakage
      - Eventually will dissolve in water
      - Thus, safety has been a concern for some

How Can Further Innovation Help?

- Zero-carbon options for processes that cannot run on electricity
  - Carbon capture and storage (a/k/a carbon sequestration)
    - Carbon is captured and stored underground or used in an industrial process
    - Storage space is an issue
  - Because of economies of scale, only appropriate for large emitters, such as power plants
  - New technologies would remove CO2 from the air ("direct air capture")
    - These technologies are still very expensive
      - Require lots of energy: will that be carbon-free?
    - As a result, firms are reluctant to invest in the technology
      - Occidental's plant would sell carbon credits to generate revenue

How Can Further Innovation Help?

- Zero-carbon options for processes that cannot run on electricity
  - Hydrogen
    - Obtained by splitting water into hydrogen and oxygen
      - However, this process is energy-intensive and has high fixed costs
      - Could be used to balance grid: ramp up electrolyzers when there is excess electricity
      - Only makes sense in applications where electricity cannot be used directly
        - » Examples include heavy duty transportation and industry
        - » Already used in some industries, but with hydrogen produced using fossil fuels

How Can Further Innovation Help?

- Zero-carbon options for processes that cannot run on electricity
  - Hydrogen
    - Obtained by splitting water into hydrogen and oxygen
    - Clean alternatives are more expensive
      - "Green" hydrogen uses renewable electricity as an energy source
      - "Blue" hydrogen uses fossil fuels combined with carbon capture and storage

How Can Further Innovation Help?

- Zero-carbon options for processes that cannot run on electricity
  - Hydrogen
    - Obtained by splitting water into hydrogen and oxygen
    - Clean alternatives are more expensive
    - Infrastructure needed to deliver hydrogen
      - E.g. the challenge for heavy-duty trucking: both batteries or hydrogen fuel cells will require new networks

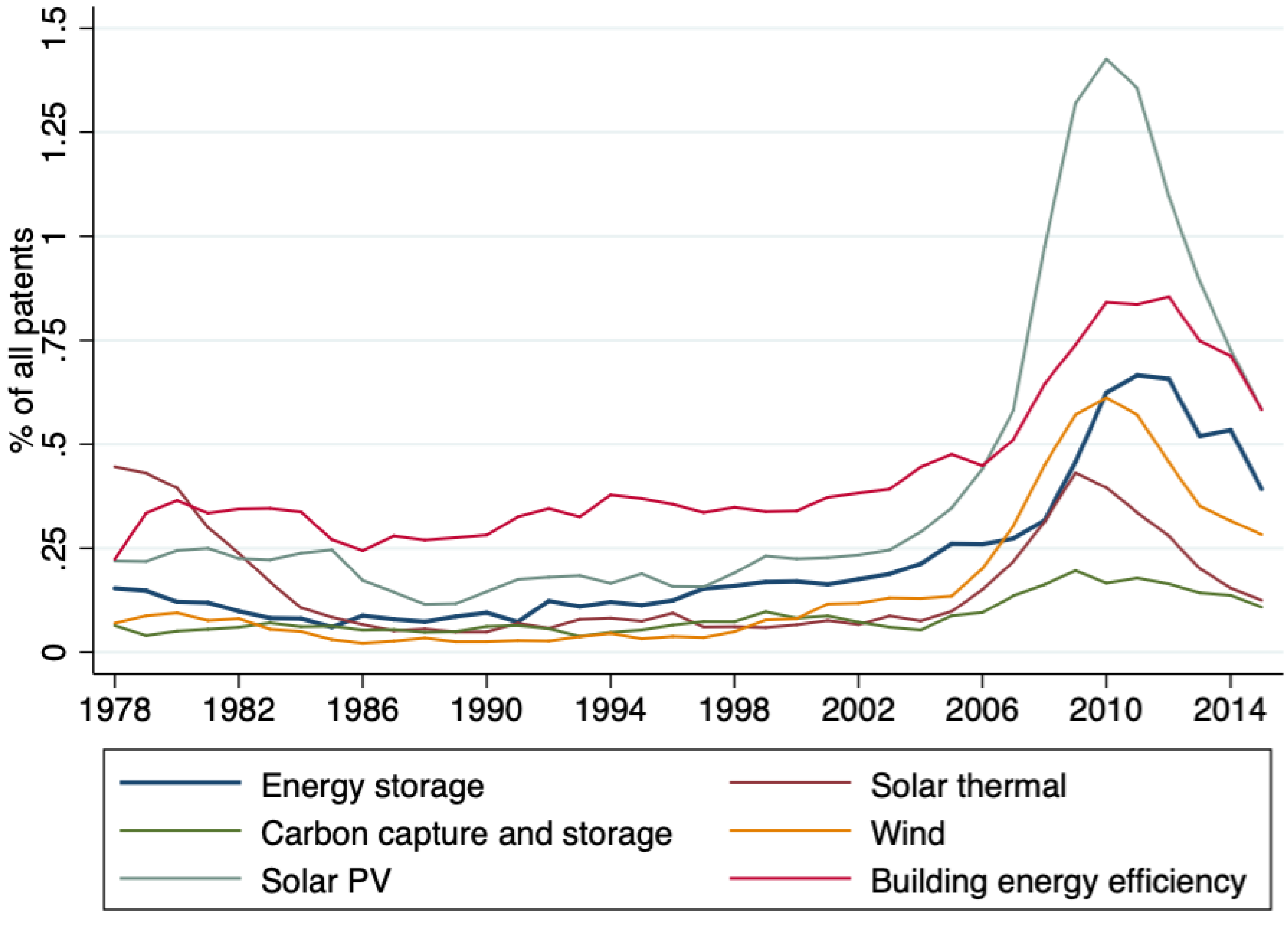
Technological Change & the Environment

- While penetration of renewable energy sources is growing, achieving significant reductions in carbon emissions requires further development and deployment

- Innovation is needed to:
  - Reduce 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

- Thus, considering how policy can promote innovation on clean technologies is important
  - Until the past few years, energy R&D efforts have remained relatively flat since the 1970s

Historical Patent Counts, Selected Energy Technologies



Source: Popp et al. (2022)

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Technological Change & the Environment

- Technological change proceeds in three stages:
  - *Invention:* an idea must be born

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  - *Innovation:* new ideas are then developed into commercially viable products
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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

- Technological change is uncertain
  - We don't know whether research will be successful, or which projects will be successful
  - This suggests that a diversified strategy is desirable
    - "Picking winners" can be costly

Technological Change & the Environment

- At all three stages, market forces provide insufficient incentives for the development and diffusion of environmentally-friendly technologies
  - *Environmental Externalities*
    - Addressed by environmental policy (e.g. *demand-pull* policies)

Technological Change & the Environment

- At all three stages, market forces provide insufficient incentives for the development and diffusion of environmentally-friendly technologies
  - *Environmental Externalities*
  - *Knowledge as a Public Good*
    - New technologies must be made available to the public for the inventor to profit
      - When this happens, some or all of the knowledge that makes up the invention also becomes available to the public.
    - Public knowledge may lead to *knowledge spillovers*—additional innovations, or even to copies of the current innovations, that provide benefits to the public as a whole, but not to the innovator
    - Addressed by science and technology policy (e.g. *technology-push*)
      - May be general (IP) or specific (subsidies for renewable R&D)

Technological Change & the Environment

- Implications of knowledge spillovers:
  - Underprovision of R&D
    - Firms invest in R&D until the marginal private rate of return equals the marginal cost
    - Thus, even if environmental externalities are corrected, there will still be insufficient R&D
      - Studies typically find that the social returns to R&D are about 4X higher than the private returns to R&D.

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      - Studies typically find that the social returns to R&D are about 4X higher than the private returns to R&D.
  - Opportunity costs are important
    - This high social rate of return is true for all R&D, not just environmental R&D
    - Thus, if we design policy to enhance environmental R&D, we must consider where those resources come from

General Innovation Policies

- Because of the public goods nature of knowledge, government policies are used to foster invention and innovation:
  - Intellectual property rights (e.g. patents, copyrights)
    - Give inventors a temporary monopoly, which enables them to capture more of the returns to their invention
      - In return, the patent document makes the invention public
      - As such, not every inventor chooses to patent an invention
    - Because of the temporary monopoly, patents encourage innovation, but slow diffusion

General Innovation Policies

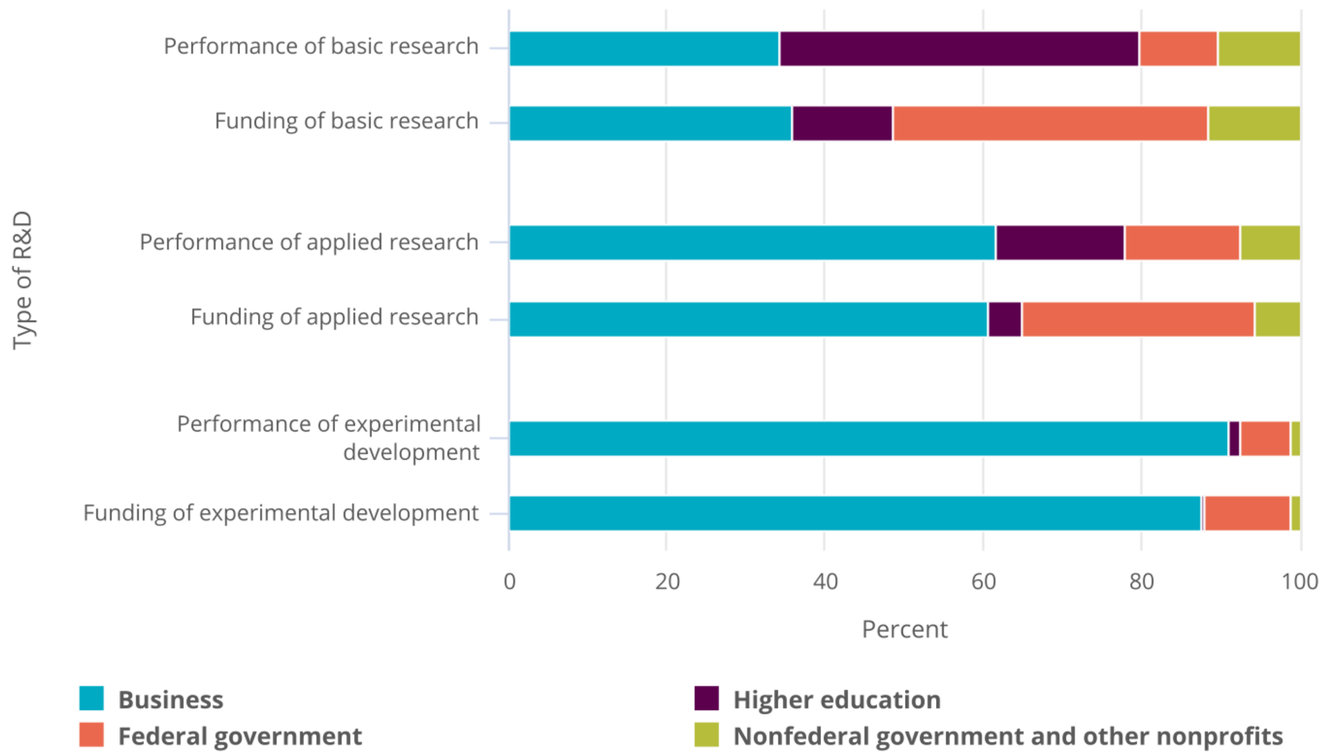
- Because of the public goods nature of knowledge, government policies are used to foster invention and innovation:
  - Government R&D funding
    - The government can provide research funding to firms and universities, or can perform research itself in government laboratories
      - Many of the government laboratories are for the Department of Energy (DOE)
    - 2022 Data
      - Federal R&D funding $159.8 billion (18% of total US R&D)
        - » $47.0 b performed directly by govt.
        - » $27.3 b performed by industry
        - » $25.8 b performed by FFRDCs
        - » $47.7 b performed by universities
        - » $11.7 b performed by nonprofits

General Innovation Policies

- Because of the public goods nature of knowledge, government policies are used to foster invention and innovation:
  - Government R&D funding
    - Government funding gives the government more control over the type of R&D done.
    - Government funding is particularly useful when spillovers are large
      - For example, basic research that cannot be patented and/or embodied in a proprietary product
    - Basic research can complement research done by firms
      - For example, DOE labs often include public/private partnerships to help commercialize new technologies

Figure 15

U.S. R&D performance and funding, by type of R&D and sector: 2021



Note(s):
Some data for 2021 are preliminary and may be revised later.

Source(s):
NCSES, National Patterns of R&D Resources (2021–22 edition).

Indicators 2024: R&D

General Innovation Policies

- Because of the public goods nature of knowledge, government policies are used to foster invention and innovation:
  - Tax credits
    - Tax credits lower the cost of R&D for firms
    - However, they give the government less control over the projects done
      - Firms will still choose to do the most profitable projects first, so tax credits are unlikely to stimulate basic research

General Innovation Policies

- Because of the public goods nature of knowledge, government policies are used to foster invention and innovation:
  - Prizes
    - Only paid out if a goal is met
    - If goal broadly defined, avoids "picking winners" among alternative solutions
    - Transfers risk from government to firms that do the R&D
    - If risk is significant, large prizes will be needed to get firms to take on this risk

Innovation & Environmental Policy

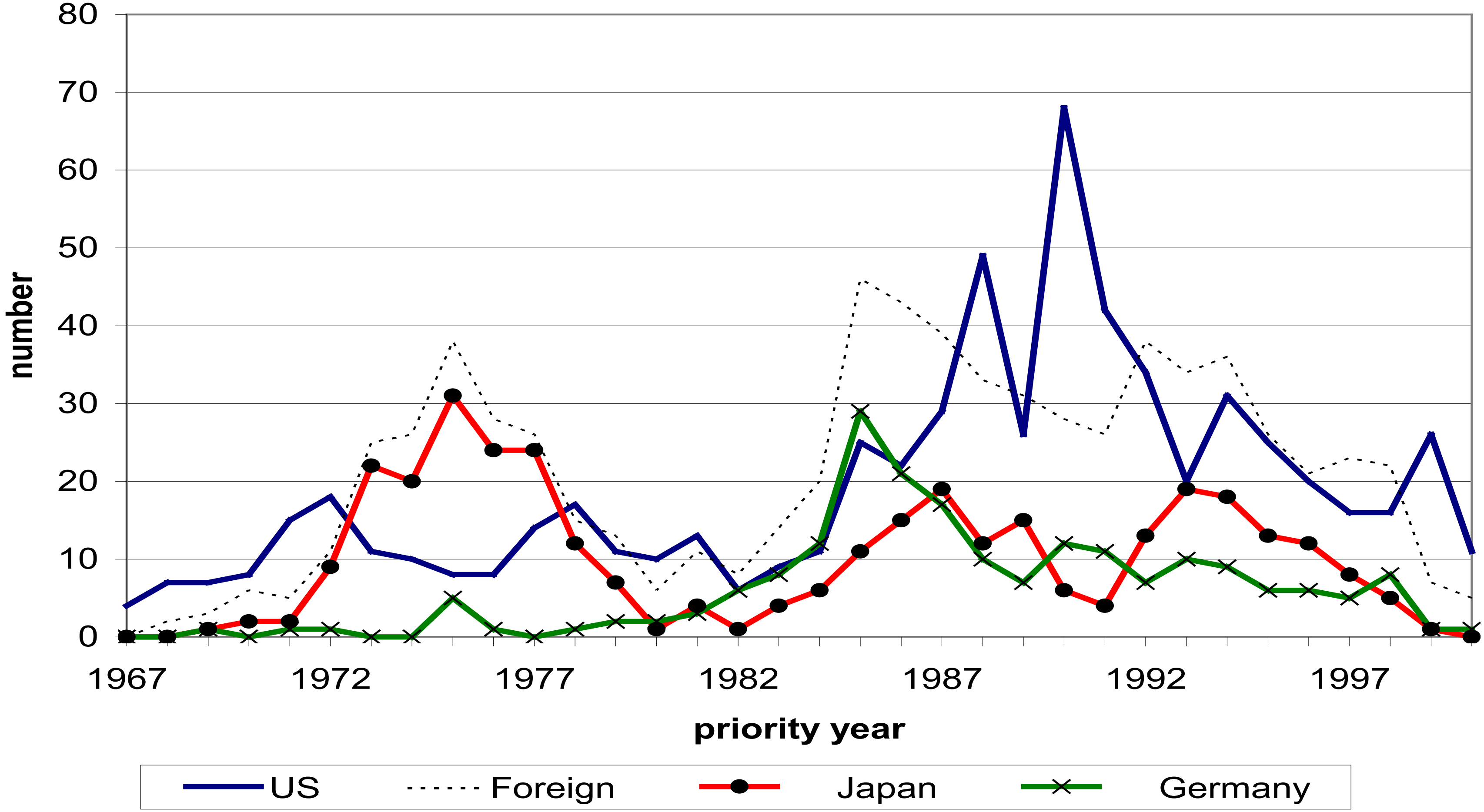
- Both environmental policy and R&D policy are needed
  - Environmental policy creates a demand for clean technologies
  - This demand creates incentives for climate-friendly innovation

- R&D policy can help lower the costs of climate policies
  - While R&D policy plays a role, it is not a substitute for environmental policy
  - R&D policy can help with the *development* of technologies, but not with the *diffusion* of technologies
    - important for innovation as well, as firms need to know there will be a market for new products

The Role of Policy: Private Sector Innovation

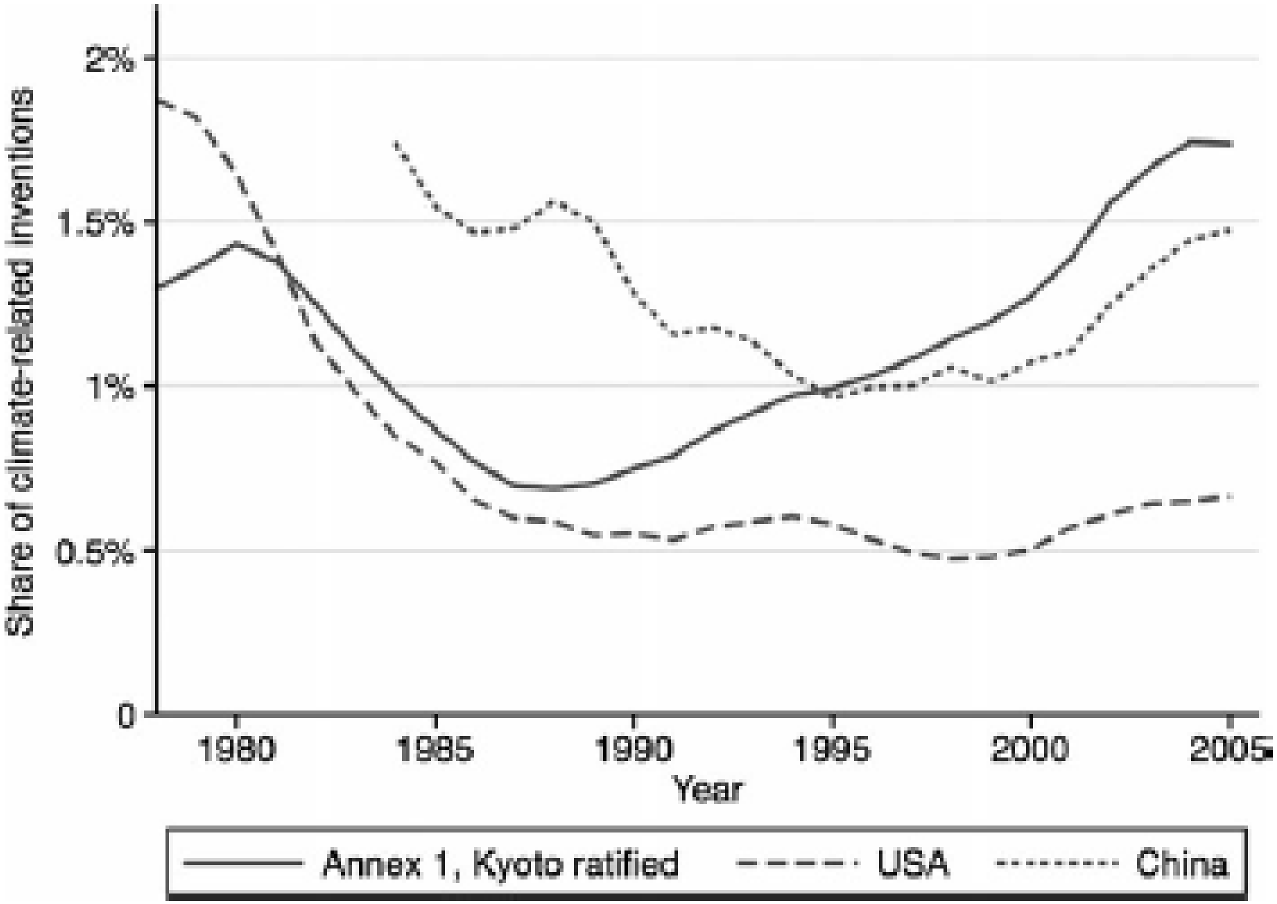
- Innovation responds quickly to incentives
  - Newell *et al*. (1999) & Popp (2002) both find most of the response of R&D to higher energy prices occurs within 5 years
  - Responses to policy are even faster

U.S. NO_X Post-Comb. Treatment Patents



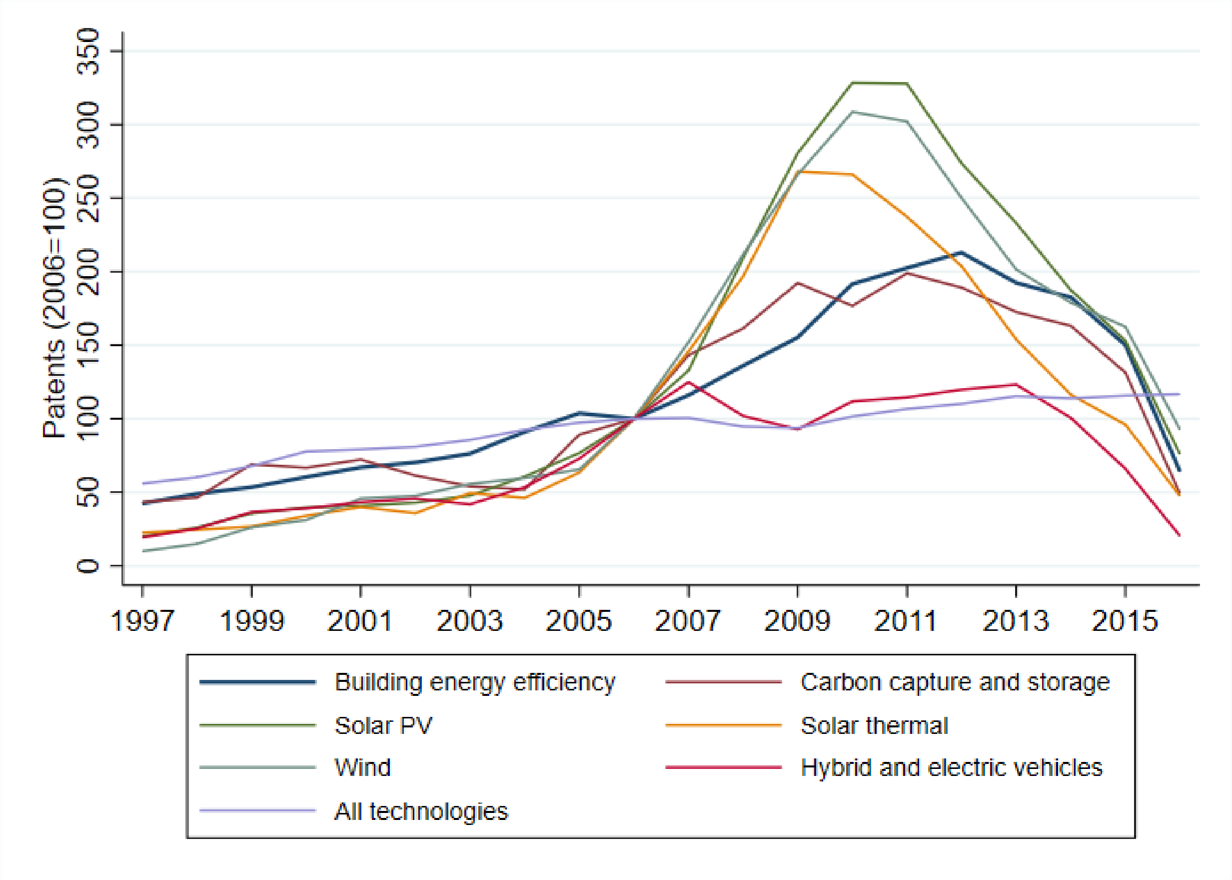
Source: Popp (2006)

Innovation and Climate Policy



Source: Dechezleprêtre *et al*. (*REEP*, 2011)

Clean energy patents over time



Source: Popp et al. (2022)

The Role of Policy: Private Sector Innovation

- Higher energy prices help encourage investment in alternatives, but they are not a substitute for environmental policy
  - Energy efficiency innovations may cause a rebound effect
  - Higher energy prices also encourage the search for more fossil fuels. Some of these, such as oil sands, even produce more carbon emissions.
  - In contrast, policies addressing emissions change the relative price of fossil fuels, so that cleaner sources become more competitive.
- *Question:* How might the current energy shock be different?

Which Policy Instruments?

- 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

Which Policy Instruments?

- 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

Which Policy Instruments?

- Policies that let the market "pick winners" will focus research efforts on technologies closest to market (Johnstone *et al*. 2010)
  - Renewable energy mandates => wind innovation
  - Guaranteed prices (e.g. feed-in tariffs) => solar innovation
    - Consider, for example, solar energy in Germany
- However, policies that promote specific technologies may increase short-run compliance costs
  - Government R&D emerges as an option to support long-term research needs

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Which Policy Instruments?

- Solutions?
  - Use government R&D to support long-term research needs (Acemoglu et al., *JPE* 2016)

  - Combine broad-based policies with limited subsidies for technologies furthest from market (Fischer *et al.*, *JAERE* 2017)
    - Most effective if target other market failures

Which Policy Instruments?

- 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 can help overcome funding hurdles
      - US Dept. of Energy SBIR grant recipients 2X as likely to receive subsequent venture capital, produce more patents, & earn more revenue (Howell, *AER* 2017)

Which Policy Instruments?

- The presence of other market failures inform policy choice
  - Capital market failures
  - Path dependency
    - Two issues
      - Network effects: 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

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          ⇒early adopters of electric vehicles provide external benefits through network effects, justifying subsidies
      - Path dependent innovation: Existing knowledge matters
        - » Prior success in fossil fuel research makes it more difficult for new technology to compete

Which Policy Instruments?

- 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; Tang, *Energy Policy* 2018)
      - Nemet (*JPAM* 2012): LBD exists , but learning is subject to diminishing returns and decays quickly
      - Fischer *et al*. (*JAERE*, 2017): R&D market failures more important than LBD, so R&D spending more effective than targeted deployment policies
        - » But current U.S. policies favor deployment

Which Policy Instruments?

- 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

The Public Sector: The Role of Energy R&D

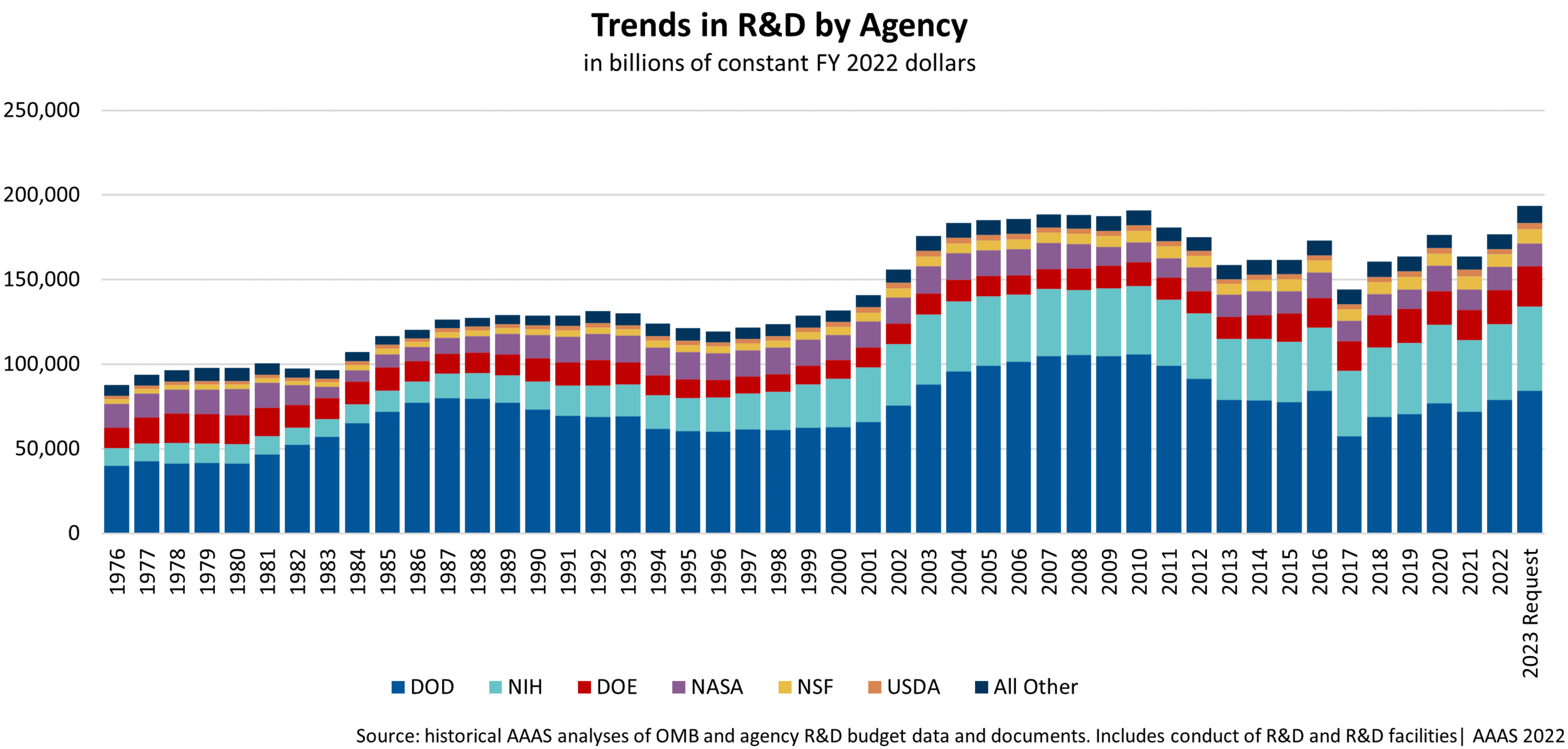
- Innovation market failures require government support for R&D
  - Federal R&D spending
    - Government funds particularly useful for basic research
    - Want to avoid duplicating what the private sector is working on
    - Even for applied research, there are some end use technologies that serve a public good, and thus will not be pursued by private industry
      - Storage of nuclear waste
      - Testing repositories for carbon dioxide sequestration
      - Improving the electrical grid to manage intermittent flows from wind and solar

The Public Sector: The Role of Energy R&D

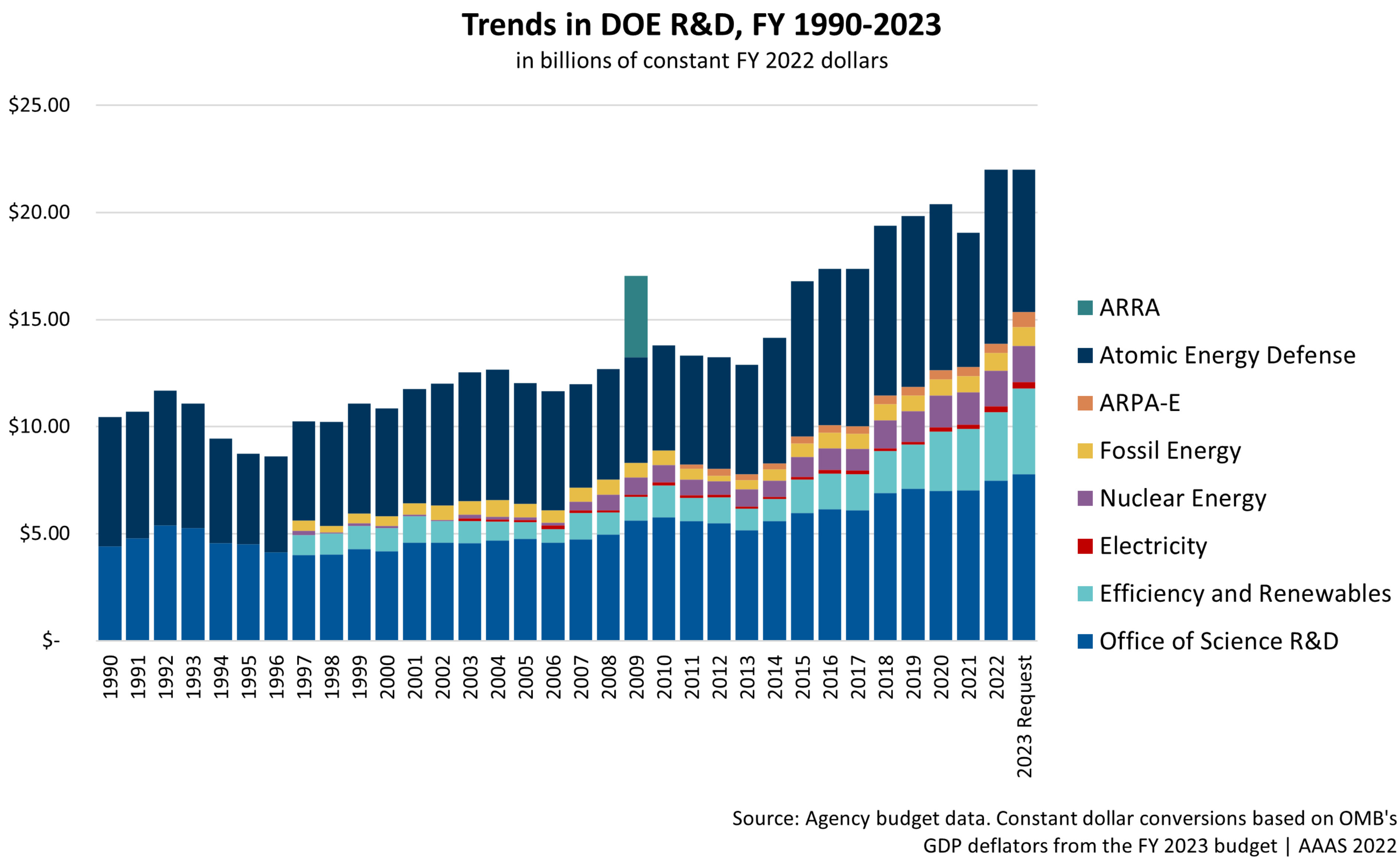
- Innovation market failures require government support for R&D
  - Federal R&D spending
    - Adjustment costs are important
      - Limits to how much we can spend on green R&D are likely to come not from the number of deserving projects, but rather from limits of the existing research infrastructure
      - US NIH experience is an example
        - Budget doubled between 1998-2003
        - Adjustment costs were high (including NIH administrative costs)
        - Funds were then cut
          - » Real NIH spending 6.6% lower in 2007 than in 2004
          - » More competition for jobs among recent post-docs
          - » Researchers spend more time writing grants

The Public Sector: The Role of Energy R&D

- Historically, energy R&D in the U.S. has focused on increasing energy supplies
  - Dramatic increases in the amount of recoverable resources have occurred
  - Motivated by goals of energy security and lowering prices
  - Civilian nuclear energy was developed as a result of military R&D investments
    - Rapid growth occurred in 1970s, before Three Mile Island
    - High capital costs are also a concern
    - Nonetheless, research on nuclear continues



Source: AAAS, http://www.aaas.org/page/historical-trends-federal-rd



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The Public Sector: The Role of Energy R&D

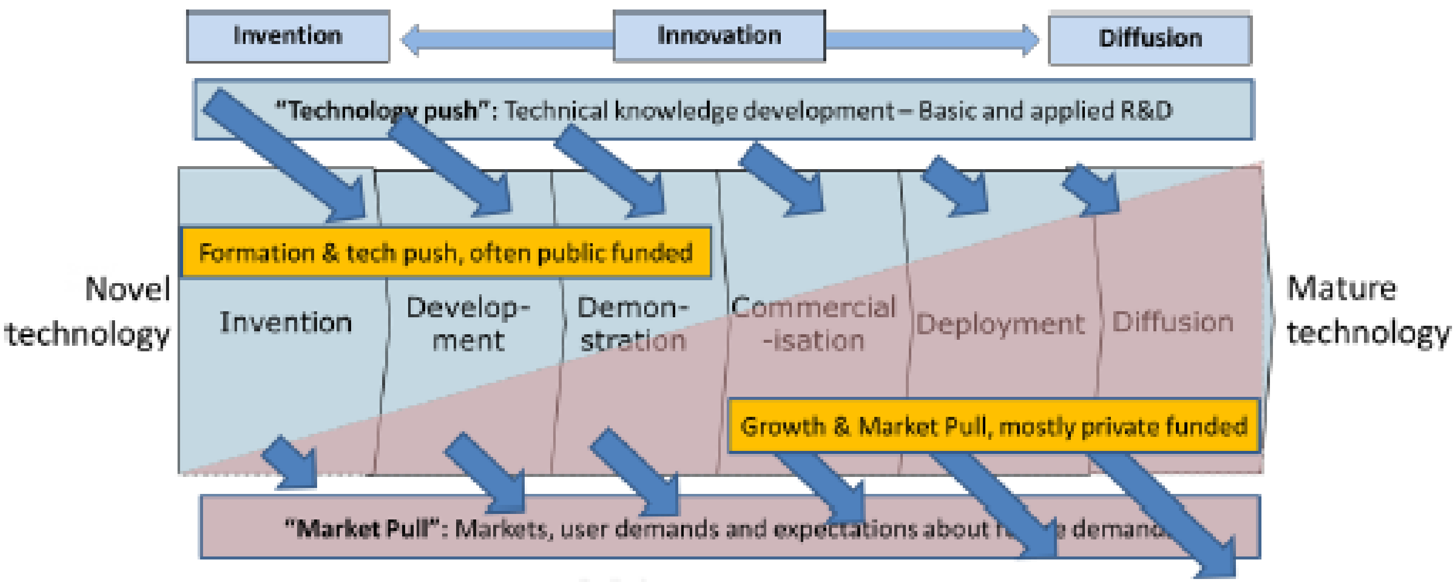
- Many early energy investments went to large scale projects that did not materialize
  - Synfuels are a failed example from the 1970s
  - However, consider that uncertainty is a part of R&D
    - Note that government can diversity risk better than private sector
  - NRC study: While only a handful of DOE programs from 1978-2000 were successful, those that were had benefits high enough to justify the cost of the entire R&D portfolio
    - The successful projects were primarily energy efficiency (refrigerators, CFL)
    - Efforts to develop energy supplies were not successful ($6 billion costs vs. $3.4 billion benefits)
      - Focused on a narrow set of technologies
      - Funding continued for political reasons even after early failures

The Public Sector: The Role of Energy R&D

- 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

The Public Sector: Technology Transfer

- Technology transfer is also important
  - A common concern among energy experts is the "Valley of Death"
    - Projects reach demonstration stage, but are not able to improve sufficiently to become commercialized



Source: Grubb et al. (*Environmental Research Letters*, 2022)

The Public Sector: Technology Transfer

- Raising private capital for clean energy technology can be difficult. Why?

The Public Sector: Technology Transfer

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  - Energy innovations take longer to get to market (Popp, *Res. Policy*, 2017)
  - Often have large fixed costs
  - Difficulty with product differentiation may make large returns unlikely (van den Heuvel and Popp, *NBER WP*, 2022)
    - Tesla vs. solar panels

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    - US Dept. of Energy SBIR grant recipients 2X as likely to receive subsequent venture capital, produce more patents, & earn more revenue (Howell, *AER* 2017)
  - However, demand still matters
    - Early stage ARPA-E awards did not increase probability of exit (Goldstein *et al*., *Nature Energy*, 2020)
    - Changing policy expectations affect VC investment (van den Heuvel and Popp, *NBER WP*, 2022)

The Public Sector: Technology Transfer

- Government funding can also new technologies overcome roadblocks to commercialization
  - Technology transfer increased after change in direction of energy R&D in the 1980s
    - Technology transfer slower when research is more basic or has national security implications
    - Patents that cite government patents (e.g. children) are most highly cited, suggesting technology transfer creates benefits (Popp 2006)

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    - Patents that cite government patents (e.g. children) are most highly cited, suggesting technology transfer creates benefits (Popp 2006)
  - Research on renewable energy sources produced by government institutions has been particularly helpful moving alternative energy research to an applied stage (Popp, *Research Policy*, 2017)
    - Government articles not more likely to be cited by other articles, but are more likely to be cited by other patents

The Public Sector: Technology Transfer

- How does government R&D aid commercialization?
  - Helps new energy technologies overcome roadblocks to commercialization (Mowrey et al., *Research Policy* 2010, Weyant, *EngEcon* 2011)
    - Large capital expenses leave a role for collaboration with the public sector to both provide support for initial project development and for demonstration projects
    - Advances in wind turbines were aided by U.S. Department of Energy-sponsored innovation on multiple turbine components
      - Funding complemented private sector efforts and allowed for feedback between public and private sector researchers

Which mix of policies should be used?

- While R&D policy plays a role, it is not a substitute for environmental policy
  - Popp (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 (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
    - However, a portfolio of policies, including R&D subsidies, outperforms any single policy
  - Fisher *et al*. (2017)
    - R&D market failures more important than LBD
    - Thus, R&D spending more effective than targeted deployment policies
    - But, current policy favors deployment