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)
        - » True long-term storage (beyond a few hours) is
    - 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
      - U.S. hydrogen subsidies larger for green hydrogen

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

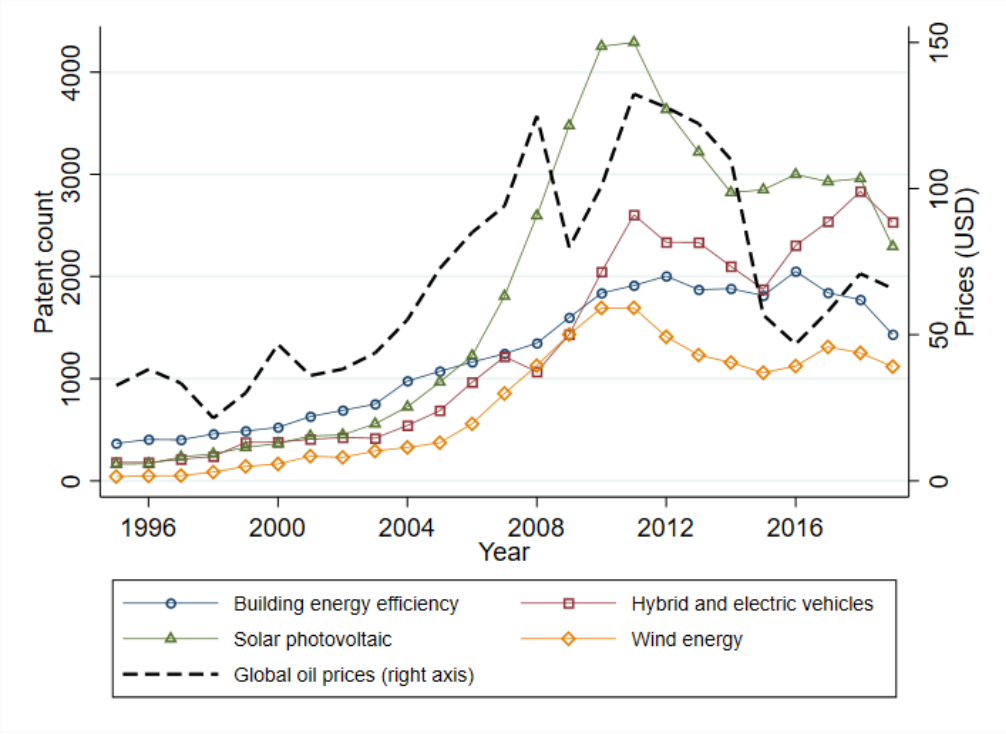
- While penetration of renewable energy sources is growing, achieving significant reductions in carbon emissions requires further development and deployment

- 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

Clean Energy Innovation Trends

Figure 1: Global Low-carbon Energy Patents



Notes: Figure shows global counts of energy patents for patents filed in two or more countries. Patents are sorted by priority year. Patent extractions from the EPO World Patent Statistical Database (PATSTAT). Oil price data are $/barrel, in 2022 US dollars, taken from the US Energy Information Administration, Short-Term Energy Outlook, June 2022.

Source: Popp *et al*. *(Review of Environmental Economics and Policy,* 2024)

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Clean Energy Innovation Trends

- What explains the decline after 2010? Possible explanations include (Popp *et al.*, 2022):
  - Falling prices
  - The role of fracking
  - Weaker than expected regulations
  - 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)

Technological Change & the Environment

- Can the success of solar energy provide lessons for other technologies?
- *Question*: What made solar R&D successful?
- *Question*: Can the conditions that made solar R&D successful be applied to other clean technologies?

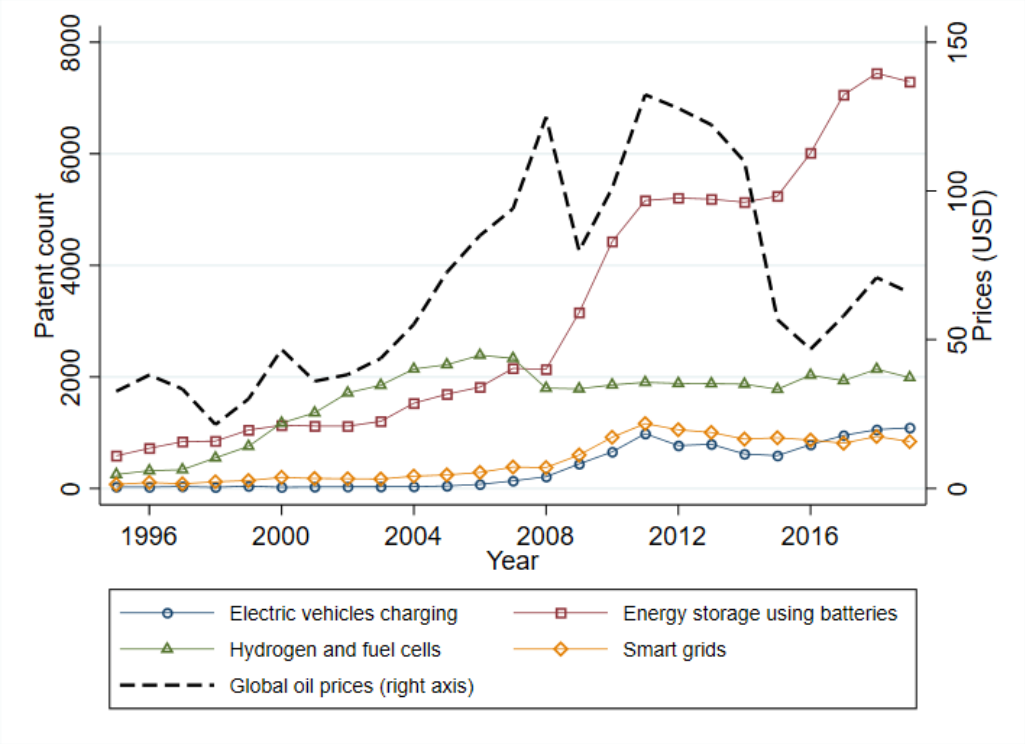
Clean Energy Innovation Trends

- Historically, policy to support innovation focused on lowering costs
  - Wind and solar were competing with fossil fuels

- Today's landscape is more complicated
  - Renewables are cost competitive in many settings
  - But further innovation is needed, particularly for enabling technologies

Clean Energy Innovation Trends

Figure 2: Global Enabling Technology Patents



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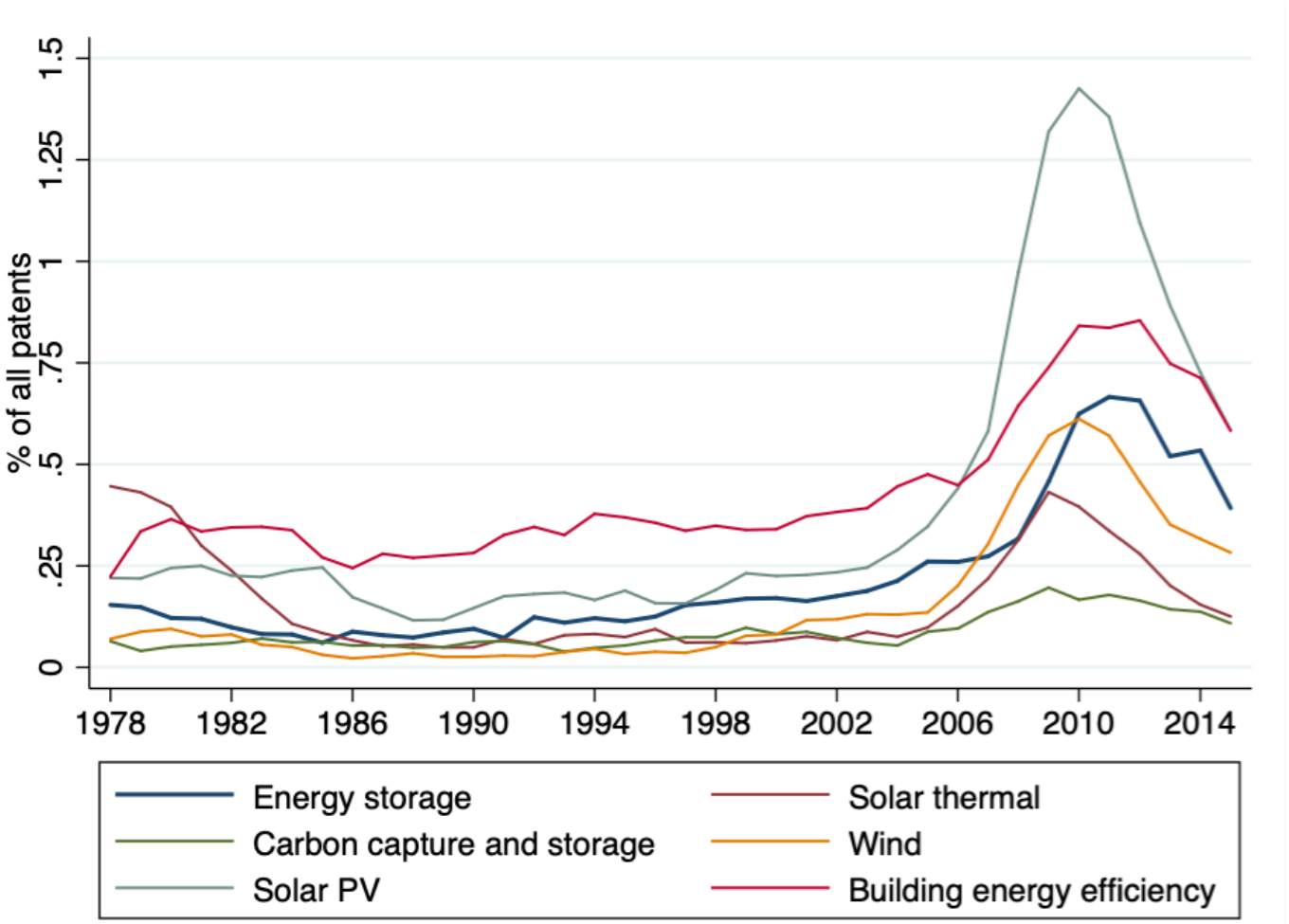
Historical Patent Counts, Selected Energy Technologies



Source: Popp et al. (2022)

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.
  - 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

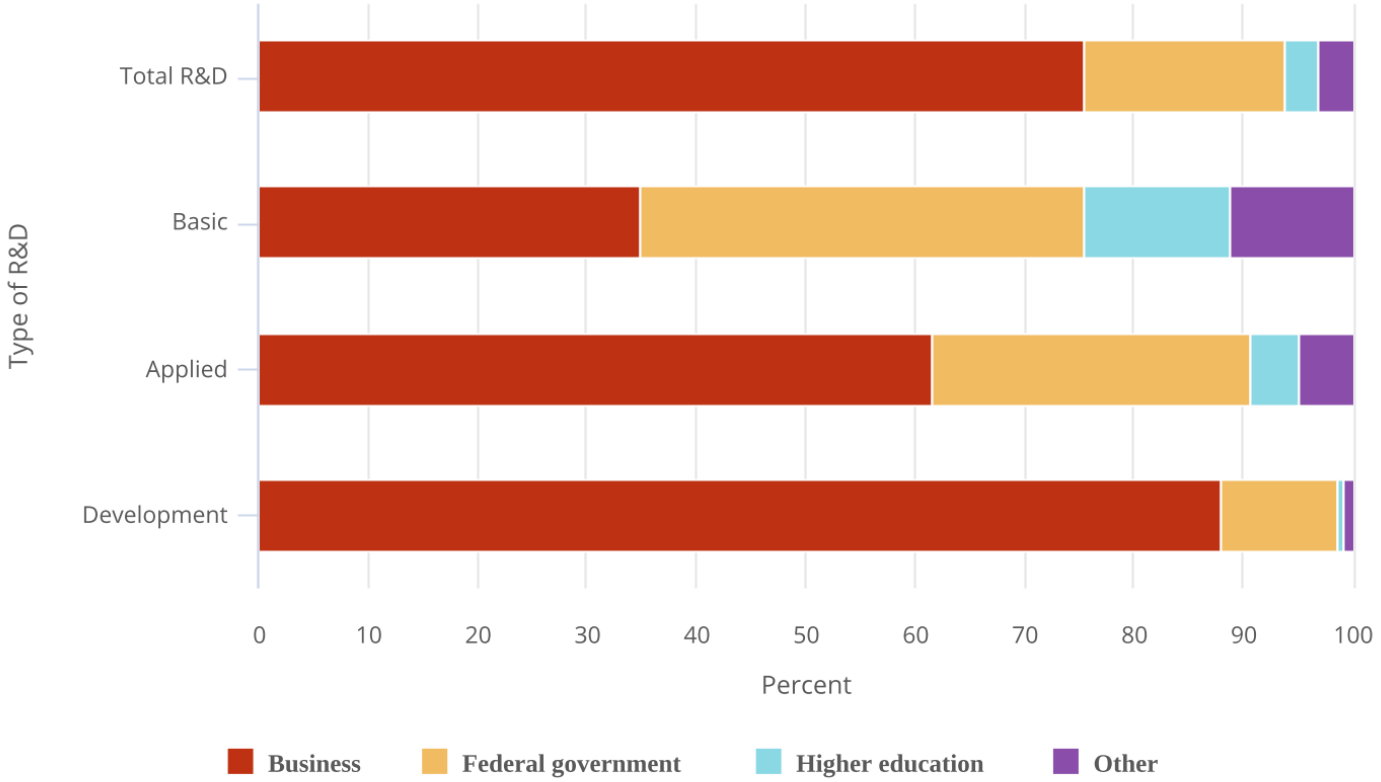
General Innovation Policies

- 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)
    - 2024 Data
      - Federal R&D funding $186 billion (19% of total US R&D)
        - » $48.5 b performed directly by govt.
        - » $35.5 b performed by industry
        - » $31.4 b performed by FFRDCs
        - » $57.2 b performed by universities
        - » $13.0 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 DISC-6. U.S. R&D, by type and funding source: 2023



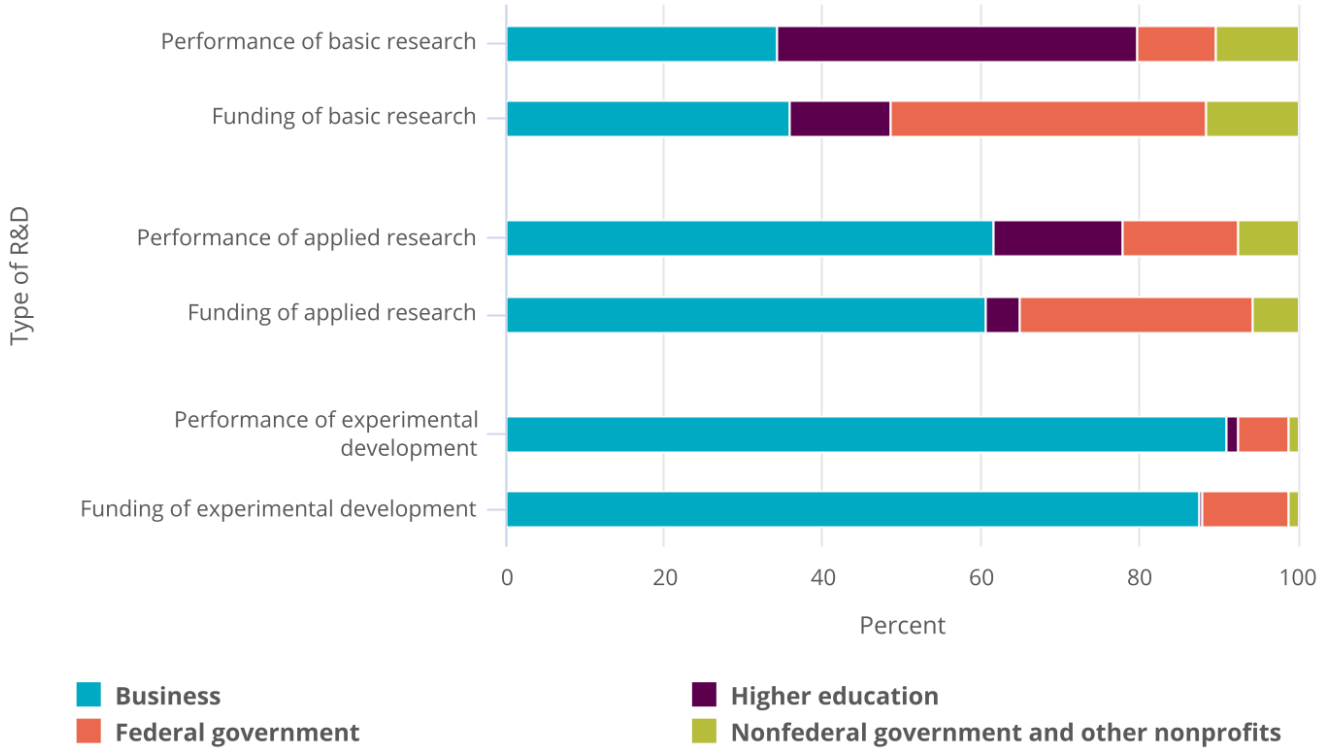
Note(s):
The data for 2023 are estimates and are likely to be revised later. R&D funding listed as Other combines data from nondederal goverment (state and local) and nonprofit organizations.

Source(s):
National Center for Science and Engineering Statistics, National Patterns of R&D Resources (2022–23 edition).

Science and Engineering Indicators

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

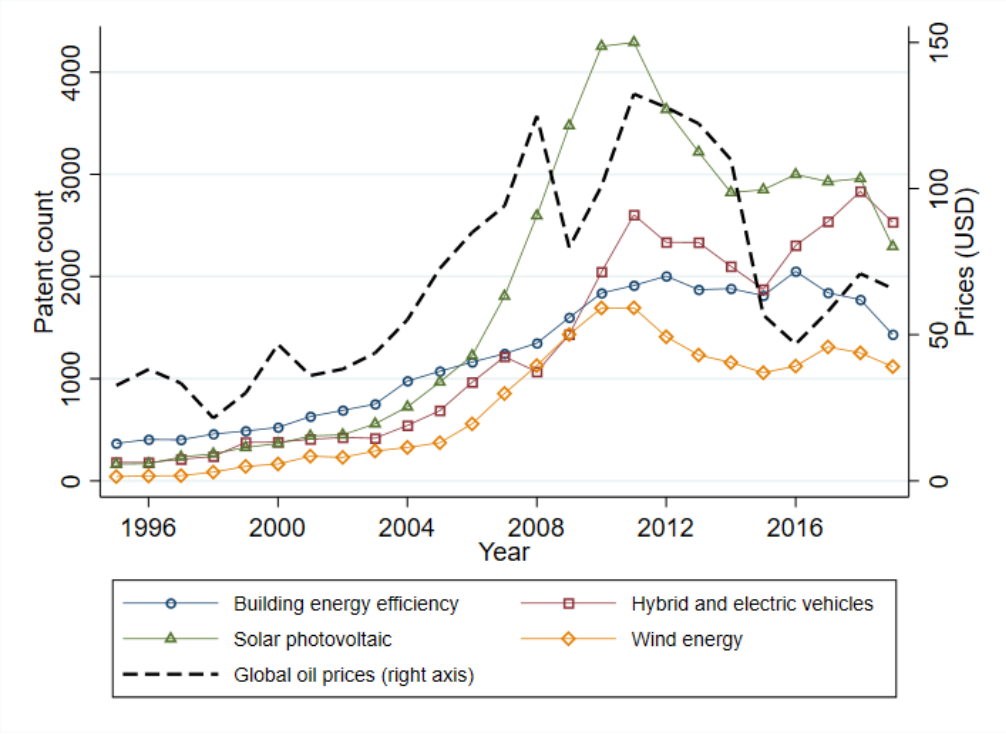
- R&D policy can help lower the costs of climate policies
  - While R&D policy plays a role, it is not a substitute for environmental policy
  - R&D policy can help with the *development* of technologies, but not with the *diffusion* of technologies
    - important for innovation as well, as firms need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

Clean Energy Innovation Trends

Figure 1: Global Low-carbon Energy Patents



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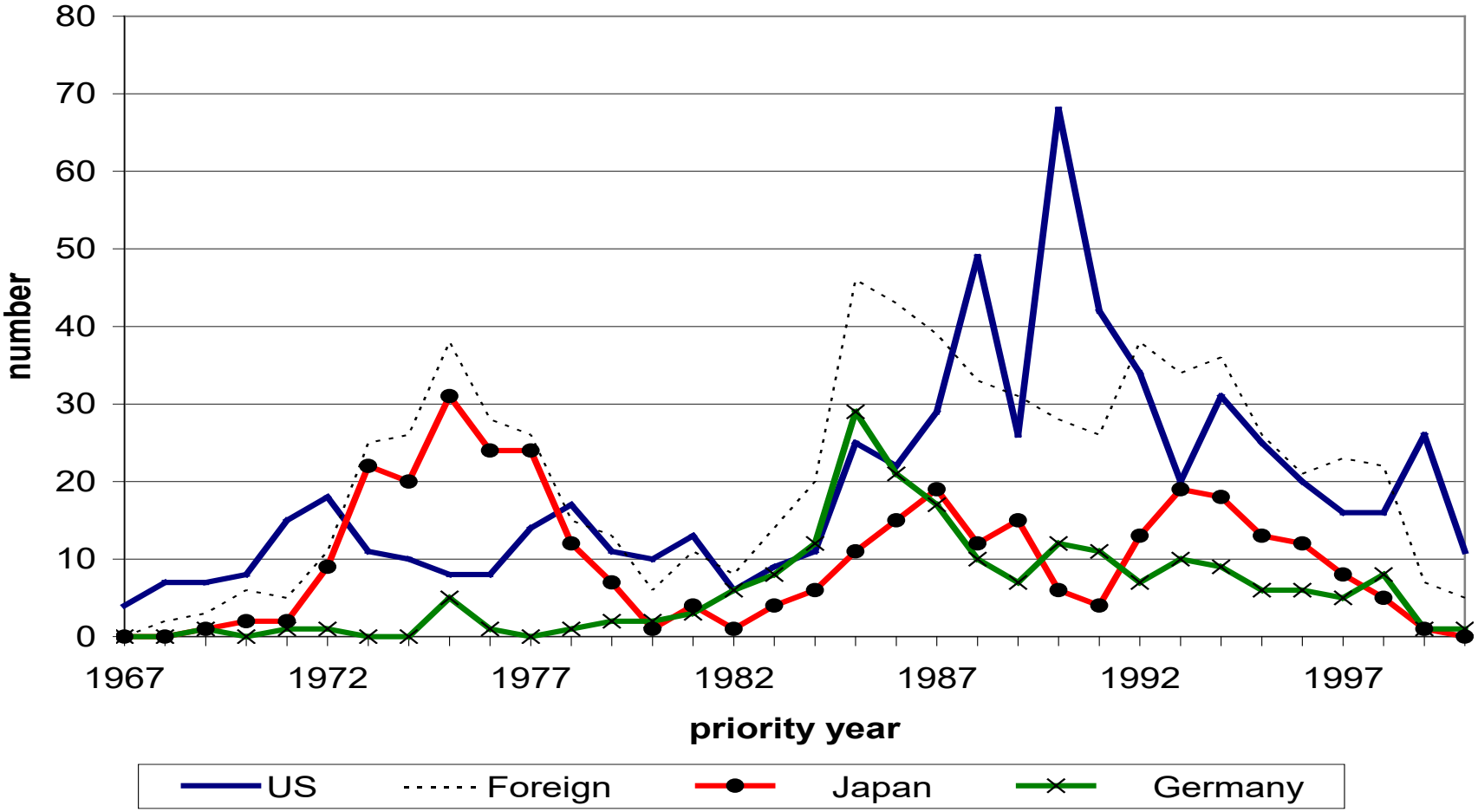
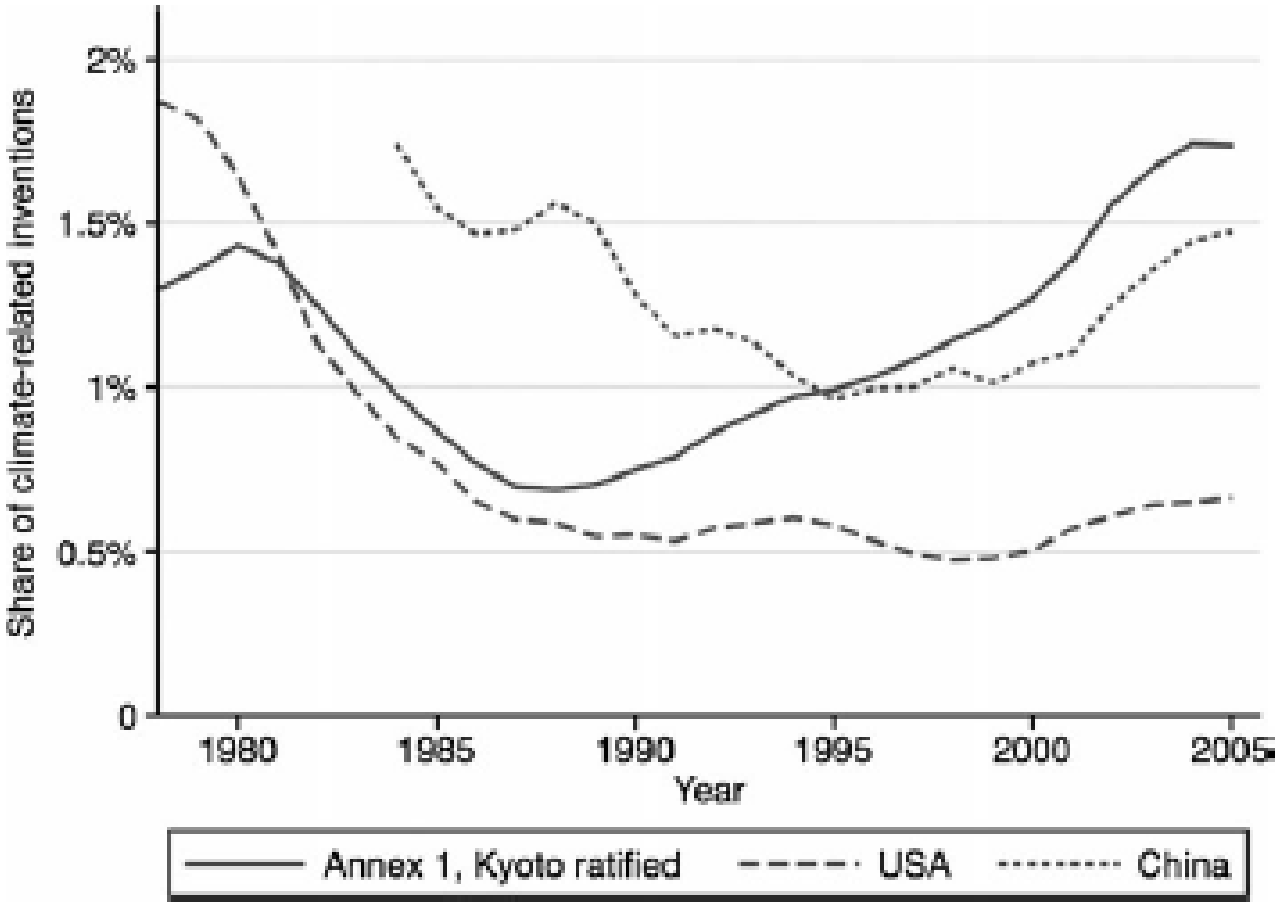
U.S. NO_X Post-Comb. Treatment Patents



Source: Popp (2006)

Innovation and Climate Policy



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

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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.

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

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

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
      - 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
  - Coordination market failures
    - Auto manufacturers and part suppliers compete in global markets. EV policy can help coordinate (Dugoua and Dumas *PNAS* 2024)
    - Technology standards help new firms enter smart grid innovation (Gregoire-Zawilski and Popp, *Research Policy*, 2024)

Which Policy Instruments?

- The presence of other market failures inform policy choice
  - Capital market failures
  - Path dependency
  - Coordination market failures
  - Learning by doing
    - Experiences of early entrants provide lessons for future technology development
    - Justifies additional deployment policies (e.g. tax credits) if there are spillovers
    - Evidence is mixed
      - When learning exists, spillovers often small (Gillingham and Bollinger, *Mgmnt Sci*, 2021) or lessons from learning decay quickly (*JPAM*, 2012)
    - Fischer *et al*. (*JAERE*, 2017): R&D market failures more important than LBD, so R&D spending more effective than targeted deployment policies

Which Policy Instruments?

- The presence of other market failures inform policy choice
  - Capital market failures
  - Path dependency
  - Coordination market failures
  - 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)
    - Gerarden (*Mgmnt Sci*, 2023): German solar subsidies => innovation that lowered costs. 86% of the benefits occurred outside Germany.
    - Myers and Lanahan (*AER*, 2022): each new patent from DOE SBIR recipients leads to three others
    - Enabling technologies more radical and more original (Popp *et al*., 2022)
    - Justifies increased government funding for clean energy R&D

The Public Sector: The Role of Energy R&D

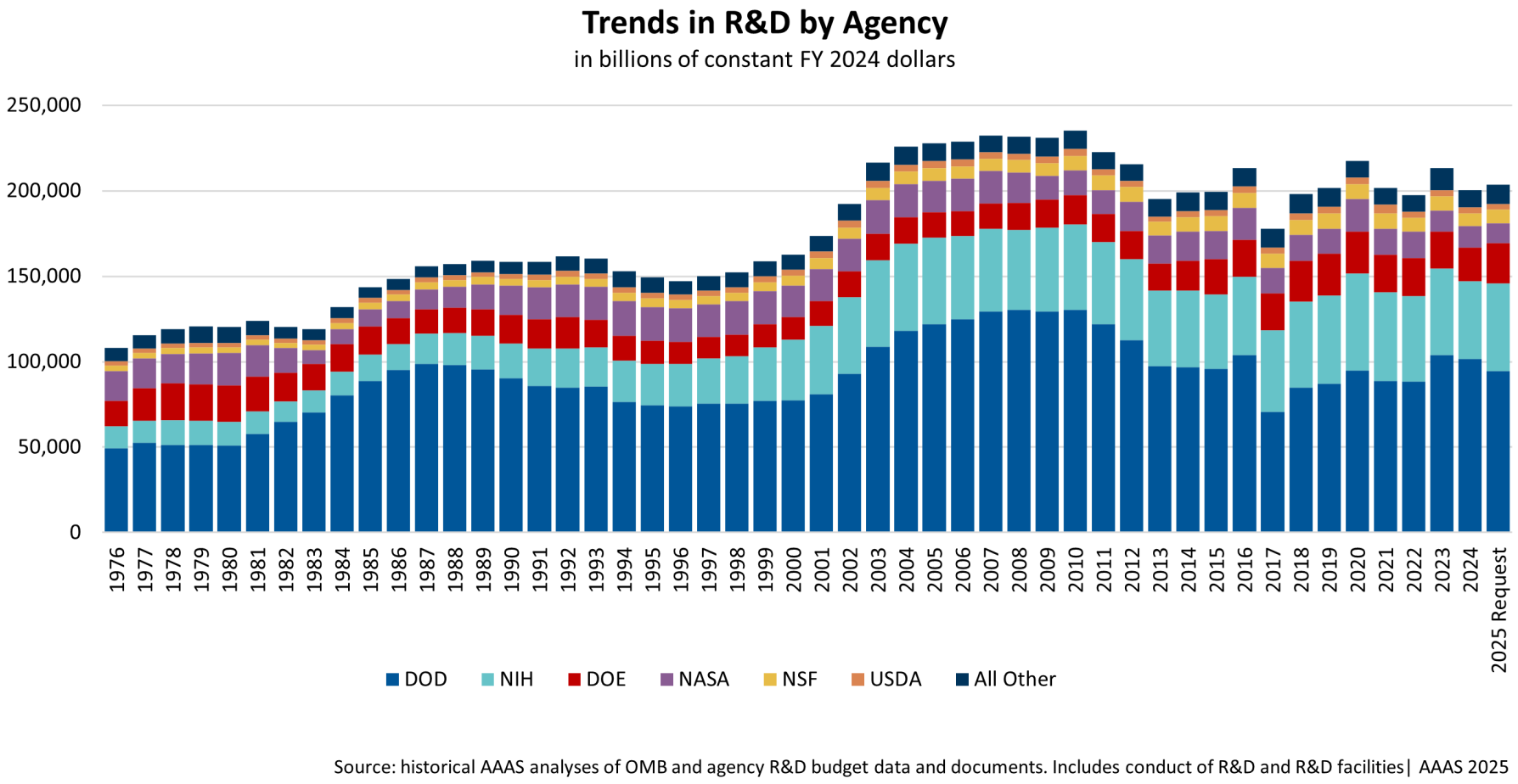
- Innovation market failures require government support for R&D
  - Federal R&D spending
    - Government funds particularly useful for basic research
    - Want to avoid duplicating what the private sector is working on
    - Even for applied research, there are some end use technologies that serve 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

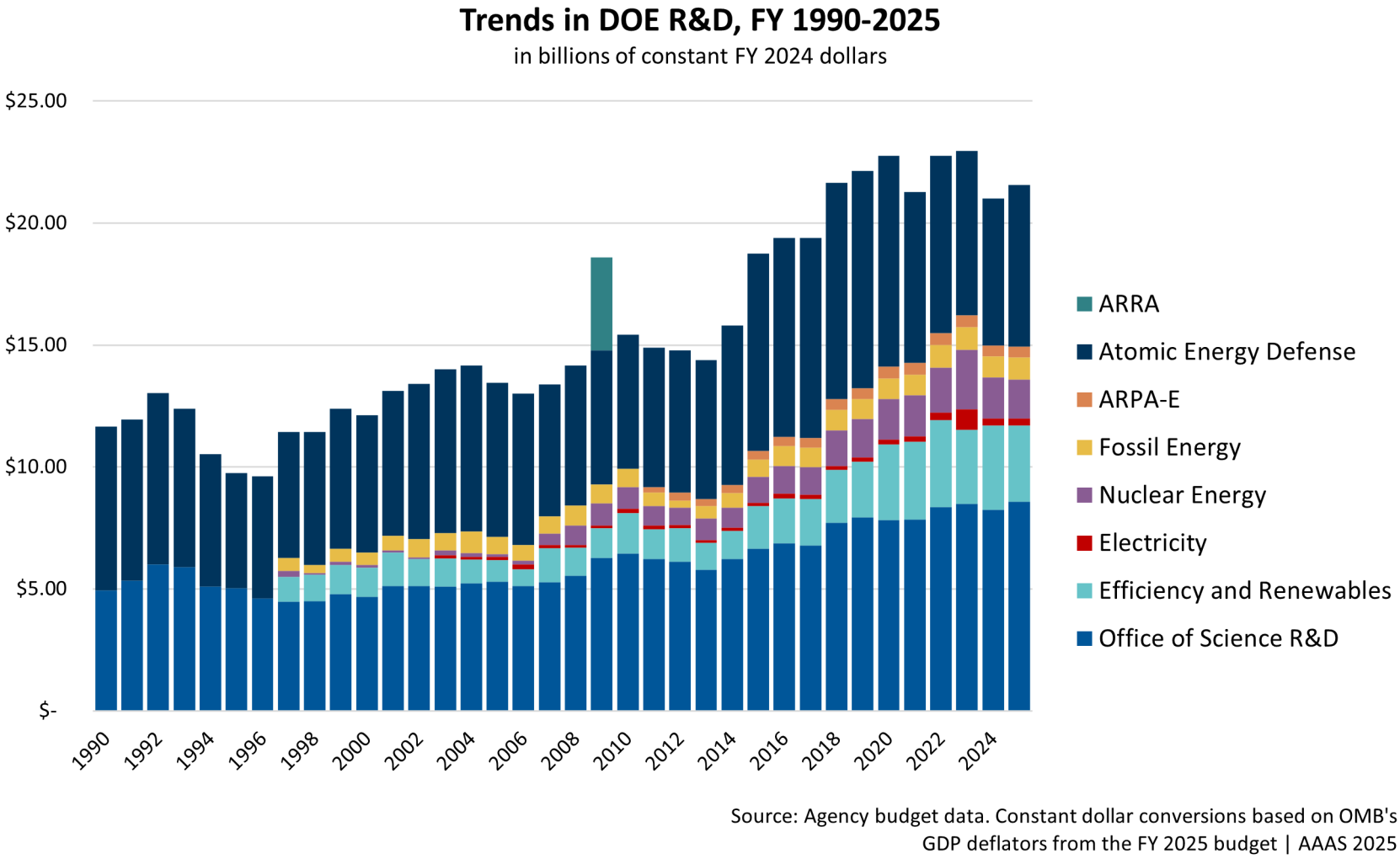
- Innovation market failures require government support for R&D
  - Federal R&D spending
    - Adjustment costs are important
      - Limits to how much we can spend on green R&D are likely to come not from the number of deserving projects, but rather from limits of the existing research infrastructure
      - 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, https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd



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The Public Sector: The Role of Energy R&D

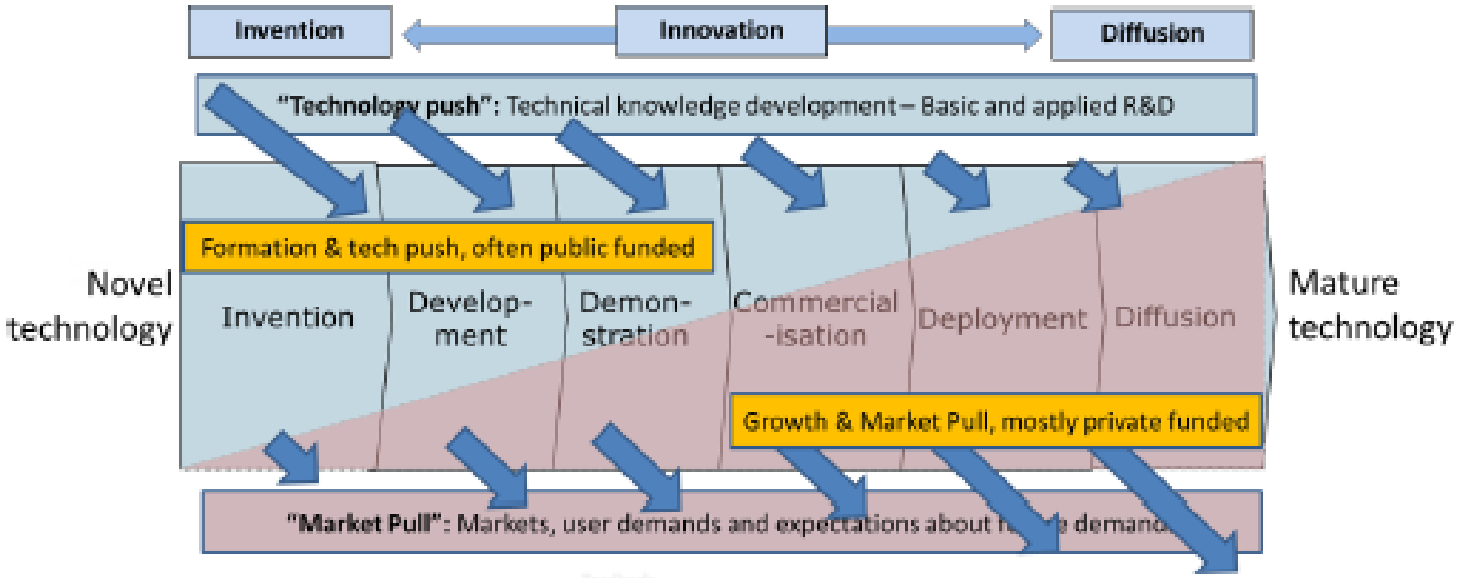
- Many early energy investments went to large scale projects that did not materialize
  - Synfuels are a failed example from the 1970s
  - However, consider that uncertainty is a part of R&D
    - Note that government can diversity risk better than private sector
  - NRC study: While only a handful of 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, *Energy Economics*, 2023)
    - Tesla vs. solar panels

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    - Tesla vs. solar panels
  - 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)
  - 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, *Energy Economics*, 2023)

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)

The Public Sector: Technology Transfer

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    - 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)
  - 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