Lecture 7:
Energy Efficiency Financing
ECO 567A

Geoffrey Barrows[1]

[1]CREST, CNRS, Ecole polytechnique

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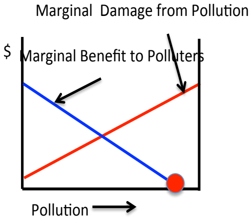
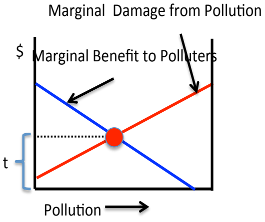
Syllabus

- Part I: Demand for Local Environmental Quality
  - Intro (Jan 10)
  - Demand I - Estimation (Jan 17)
  - Demand II - Sorting and Environmental Justice (Jan 24)
  - Amenities and Quant. Spatial Economic Models (Jan 31)
- Part II: Supply of Local Environmental Quality - Energy
  - Energy Production (Feb 7)
  - Energy Demand (Feb 14)
  - Energy Efficiency Innovation (Feb 21)
  - Trade and Pollution (March 7)
- Part III: Global Externalities
  - Climate Change (March 14)
- Final Exam March 19 9am - noon T5

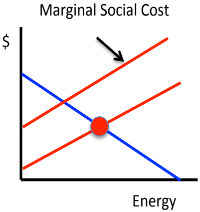
Unregulated Equilibrium

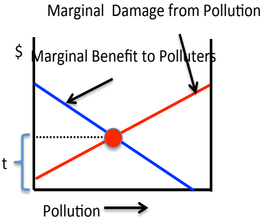


Optimal Regulation of the Environmental Good



Associated Goods





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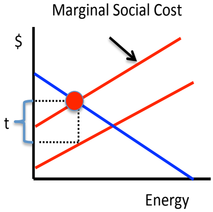

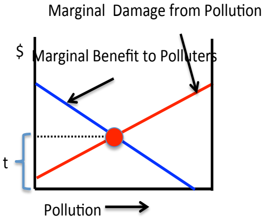

Demand for Associated Services

- We can regulate environmental goods by regulating associated goods, like energy

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$$U(light) = U(\underbrace{energy}_{\text{variable input}} * \underbrace{\frac{light}{energy}}_{\text{Efficiency}})$$

Demand for Associated Services

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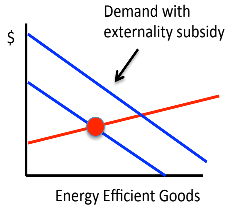
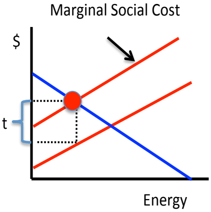
- But consumers ultimately care about associated services, not the associated goods themselves:

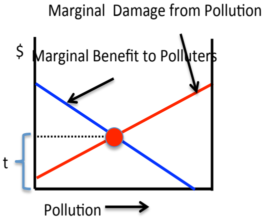
$$U(light) = U(\underbrace{energy}_{\text{variable input}} * \underbrace{\frac{light}{energy}}_{\text{Efficiency}})$$

- Instead of regulating energy consumption (which may be politically difficult), we can reduce environmental damage by regulating the demand for energy efficient goods

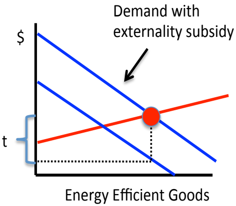
Demand for Energy Efficiency

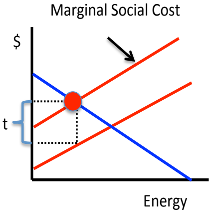


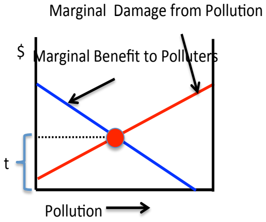




Optimal Regulation for Energy Efficiency







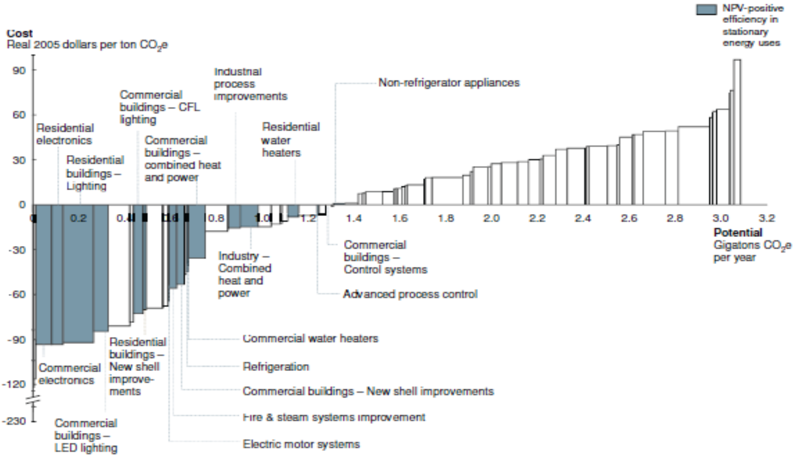
Optimal Regulation for Energy Efficiency

- Demand Side
- Supply Side

Subsidizing Energy Efficiency Demand

1. unpriced externalities
2. investment inefficiencies

McKinsey Report

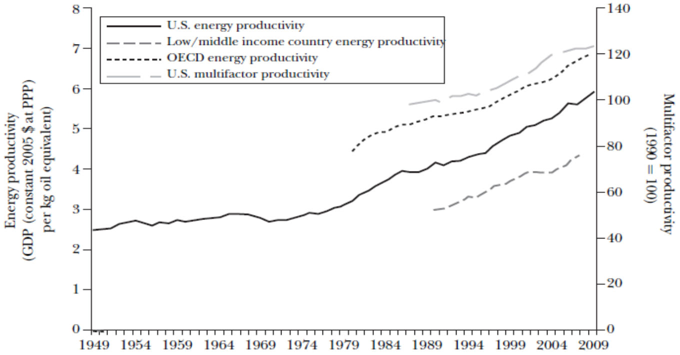


Energy Efficiency Policies

Table 2
Significant U.S. Energy Efficiency Policies

Name	*Year*	*Magnitude*
Corporate Average Fuel Economy Standards	1978–	$10 billion annual incemental cost from tightened 2012 rule (NHTSA 2010)
Federal Hybrid Vehicle Tax Credit	2006–2010	$426 million total annual credit (Sallee 2010)
Gas guzzler tax	1980–	$200 million annual revenues (Sallee 2010)
Federal appliance energy efficiency standards	1990–	$2.9 billion annual incremental cost (Gillingham, Newell, and Palmer 2006)
Residential and commercial building codes	1978–	
Electricity Demand-Side Management programs	1978–	$3.6 billion annual cost (US EIA 2010)
Weatherization Assistance Program (WAP)	1976–	$250 million annual cost (US DOE 2011a)
2009 Economic Stimulus	2009–2011	$17 billion total (U.S. DOE 2011b)
Additional WAP funding		$5 billion
Recovery Through Retrofit		$454 million
State Energy Program		$3.1 billion
Energy Efficiency and Conservation Block Grants		$3.2 billion
Home Energy Efficiency Tax Credits		$5.8 billion credit in 2009 (U.S. IRS 2011)
Residential and Commercial Building Initiative		$346 million
Energy Efficient Appliance Rebate Program		$300 million
Autos Cash for Clunkers		$5 billion

Energy Efficiency has Increased



A Model of Energy Efficiency Adoption

- Let e_0 represent energy intensity of traditional technology
- Let e_1 represent energy intensity of "efficient" technology, with $e_1 < e_0$
- Investment increases capital costs by c and user costs by ξ (e.g., Prius doesn't drive as well and looks weird)
- Every year, the consumers saves $p * m_i * (e_0 - e_1)$
- Consumer discounts the variable costs savings in the second period with discount rate $r > 0$ (like .05)

A Model of Energy Efficiency Adoption

- Under these assumptions, the agent adopts the energy efficient good iff

$$\underbrace{\frac{pm_i(e_0 - e_1)}{1+r}}_{\text{NPV of variable cost savings}} - \underbrace{\frac{\xi}{1+r}}_{\text{extra user cost of adoption}} > \underbrace{c}_{\text{relative capital cost of adoption}}$$

Adoption could be “too low” for two reasons

1. unpriced externalities

2. investment inefficiencies

1. Unpriced Externality Costs

- Let φ represent externality cost of energy consumption
- Then the condition for socially optimal investment is

$$\frac{(p+\varphi)m_i(e_0-e_1)}{1+r}-\frac{\xi}{1+r}>c$$

- With $\varphi > 0$, adoption is too low relative to social optimum

2. Investment Inefficiencies

- Let γ represent investment inefficiencies that cause the consumer to undervalue efficiency
    1. Imperfect information
    2. Inattention
    3. Credit Constraints

- Then the condition for private optimum is

$$\frac{\gamma * pm_i(e_0 - e_1)}{1+r} - \frac{\xi}{1+r} > c$$

- But the condition for socially optimal investment is

$$\frac{(p+\varphi)m_i(e_0 - e_1)}{1+r} - \frac{\xi}{1+r} > c$$

- Adoption is too low because of both γ and φ

Why are there investment inefficiencies

Imperfect Information

- People may not know how badly their homes are insulated or how to "weatherize" them

Imperfect Information

- It may be costly for renters to find out how efficient the house is, so landlords have an incentive not to invest in efficiency

Inattention

- People focus on observable features of durables

Inattention

- People focus on observable features of durables, without considering ancillary costs

Credit Constraints

- Durable goods require upfront capital. Some people may not be able to secure loans to make an energy efficient investment

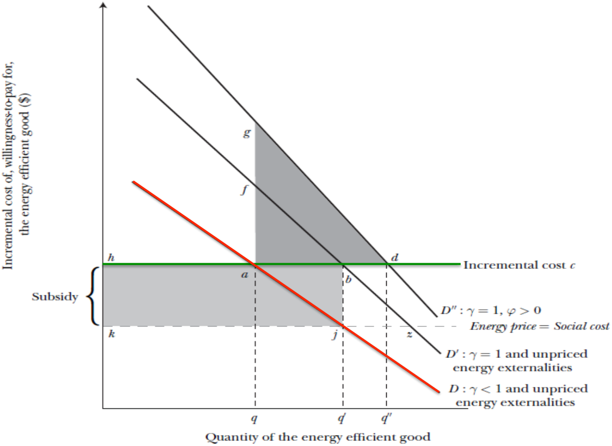
Regulating Energy Efficiency Goods

- Under-investment due to φ is basically the same problem we have been analyzing
  - The price of GHG producing goods is too low. The optimal response is just to tax energy at the rate φ, and then energy efficiency reaches the social optimum
- If $\gamma < 1$, it means that adoption is too low for reasons unrelated to environmental externalities
  - In this case, there is an "energy efficiency gap", as consumers fail to invest in capital goods which would in fact save them money overall.

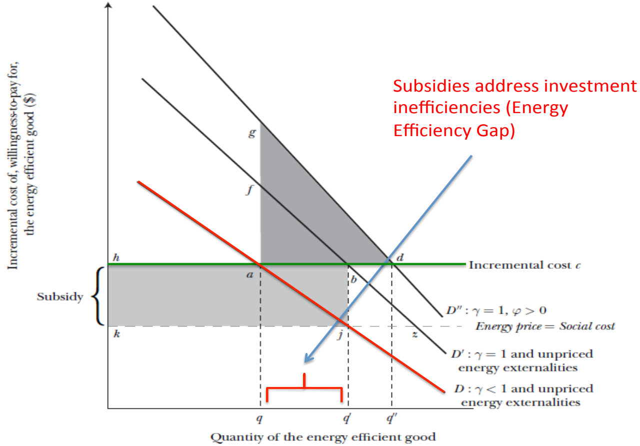
Principle of Targeting

- Tinbergen: you need as many policy tools as you have market failures
- If there are unpriced externalities and investment inefficiencies, then we need environmental taxes AND policies to reduce investment inefficiencies

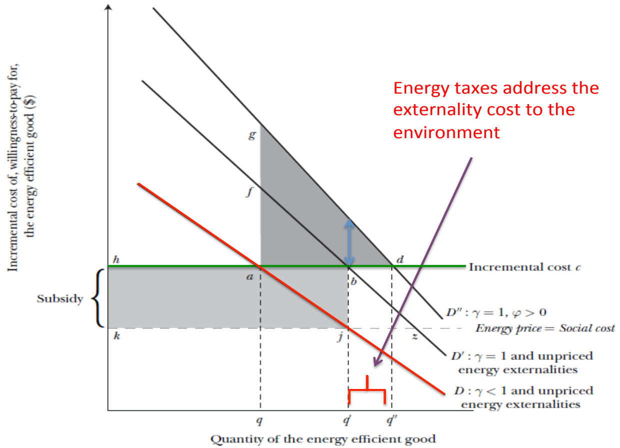
Energy Efficiency Regulation



Energy Efficiency Regulation



Energy Efficiency Regulation



Energy Efficiency as a Second-best Approach to the Environment

When no investment inefficiencies exist, energy efficiency policies will have larger welfare costs per unit of pollution abated compared to the first-best Pigouvian tax

1. Subsidies and standards change the relative price of durables for all consumers, whereas energy taxes impact high-energy users the most
2. Subsidies and standards do not provide the right incentive for utilization
    - The relative cost of energy in fact drops, encouraging more energy use (rebound)
3. It is difficult to calibrate the stringency of efficiency standards correctly, so you may not get exactly the right amount of investment and abatement

Allcott and Greenstone (2012) : Is there an energy efficiency gap?

- If there is an energy efficiency gap ($\gamma < 1$), then these policies may be a good "second-best" tool, absent externality pricing
  - They address the investment inefficiency and may help a bit with the externality
- But if there is no energy efficiency gap, then energy efficiency subsidies probably lower welfare overall

Evidence on the energy efficiency gap?

1. Engineering estimates of potential returns to investments
2. Empirical estimates of returns to observed investments
3. Cost effectiveness of energy conservation programs
4. Estimated demand patterns for energy-using durables

1. Engineering estimates of potential returns to investments

- Omit unobserved costs of adoption.

  Anderson and Newell (2004) find that nearly half of investments that engineering assessments showed would have short payback periods were not adopted due to unaccounted physical costs, risks, or opportunity costs, such as "lack of staff for analysis/implementation," "risk of inconvenience to personnel," or "suspected risk of problem with equipment."

- Engineering estimates of energy saved may be faulty

  Dubin, Miedema, and Chandran (1986), Nadel and Keating (1991), and others have documented that engineering estimates of energy savings can overstate true field returns

2. Empirical estimates of returns to observed investments

Schweitzer (2005) estimates that the average weatherization costs \$2,600 and reduces natural gas consumption by 20-25%, or about \$260 a year. Hence, if the life of the investment is less than 10 years, then savings do not pay back investment.

Additionally

- Results are based on non-experimental estimates. Perhaps adopters make other changes at the same time.
- Unobserved costs
- Heterogeneous effects. Estimates for adopters overstate returns for non-adopters.

3. Cost effectiveness of energy conservation programs

Arimura, Li, Newell, Palmer (2011) estimates that demand side management programs (mostly subsidy programs for investment)

- Conserved electricity at cost of 5 cents per kWh. (8.5 cents including user cost)
- Compared to electricity price of 9 cents per kWh
- Investments were barely profitable (The gov spends 8.5 cents to save the consumer 9 cents)
- Not very strong evidence in favor of investment frictions

4. Estimated demand patterns for energy-using durables

- Estimate demand system

$$U_{ij} = \alpha * \text{NPV Var Cost}_j + \beta * \text{Price of Car}_j + \epsilon_{ij}$$

- compute $\gamma = \alpha/\beta$
- Allcott and Wozny (2011), Busse, Knittle Zettelmeyer (2011) apply to cars and find γ close to 1.
- Not very strong evidence in favor of investment frictions

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$\Longrightarrow$ Not very strong evidence in support of energy efficiency gap

Supply

Supply of energy efficient goods might be “too low” also because of

1. Unpriced externalities

2. Investment frictions

Aghion et al (2016)

Research Question: Can energy taxes encourage development of energy efficiency goods?

- Theoretically, yes. With higher energy prices, there is higher demand for energy efficiency goods, and hence higher returns to developing new/better products
- But are firms responsive to the price signal?

Also, is development path dependent (on existing own stock and neighbor stock)?

- How long would it take clean technologies to overtake dirty technologies?

Empirical setting: Car patenting

- For car manufacturers, we can identify patents as “green” vs “brown”
- Aghion et al connect the rate of both “green” and “brown” patenting to firm-level energy prices

Aghion et al (2016)

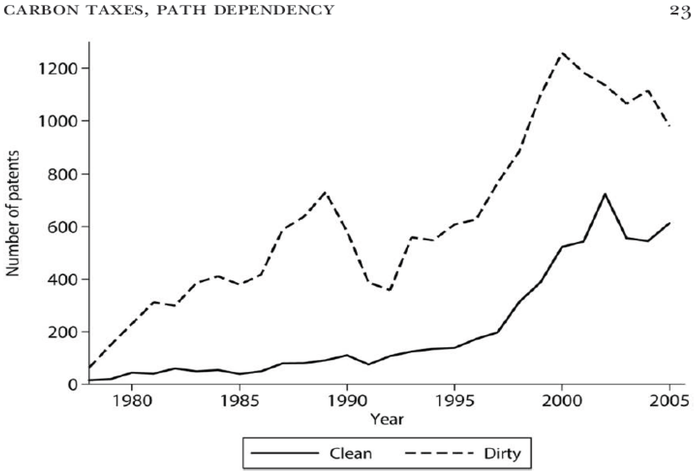
TABLE 1
DEFINITION OF IPC PATENT CLASSES FOR CLEAN AND DIRTY PATENTS

Description	IPC Code
A. Clean Patents	
Electric vehicles:	
Electric propulsion with power supplied within the vehicle	B60L 11
Electric devices on electrically propelled vehicles for safety purposes; monitoring operating variables, e.g., speed, deceleration, power consumption	B60L 3
Methods, circuits, or devices for controlling the traction–motor speed of electrically propelled vehicles	B60L 15
Arrangement or mounting of electrical propulsion units	B60K 1
Conjoint control of vehicle subunits of different type or different function/including control of electric propulsion units, e.g., motors or generators/including control of energy storage means/for electrical energy, e.g., batteries or capacitors	B60W 10/08, 24, 26
Hybrid vehicles:	
Arrangement or mounting of plural diverse prime movers for mutual or common propulsion, e.g., hybrid propulsion systems comprising electric motors and internal combustion engines	B60K 6
Control systems specially adapted for hybrid vehicles, i.e., vehicles having two or more prime movers of more than one type, e.g., electrical and internal combustion motors, all used for propulsion of the vehicle	B60W 20

Aghion et al (2016)

B. Dirty Patents	
Internal combustion engine:	
Internal combustion piston engines; combustion engines in general	F02B
Controlling combustion engines	F02D
Cylinders, pistons, or casings for combustion engines; arrangement of sealings in combustion engines	F02F
Supplying combustion engines with combustible mixtures or constituents thereof	F02M
Starting of combustion engines	F02N
Ignition (other than compression ignition) for internal combustion engines	F02P
C. Grey Patents	
Fuel efficiency of internal combustion engines:	
Fuel injection apparatus	F02M39-71
Idling devices for carburetors preventing flow of idling fuel	F02M3/02-05
Apparatus for adding secondary air to fuel-air mixture	F02M23

Aghion et al (2016)



Estimation Equation for firm i in time t

$$\begin{aligned} PAT_{it} &= exp(\beta_p * \ln FP_{i,t-1} + \beta_1 * \ln SPILL_{C,i,t-1} + \beta_2 * \ln SPILL_{D,i,t-1} \\ &+ \beta_3 * \ln K_{C,i,t-1} + \beta_4 * \ln K_{D,i,t-1} + \beta_\omega * \omega_{it} + T_t)\eta_i + u_{it} \end{aligned}$$

- Fuel prices

$$\ln FP_{it} = \sum_c w^{FP}_{ic,0} * \ln FP_{ct}$$

- Knowledge Stock for $z \in \{C, D\}$

$$K_{z,it} = PAT_{z,it} + (1 - \delta)\, K_{z,it-1}$$

- Spillover term

$$SPILL_{z,it} = \sum_c w^S_{ic,0} * SPILL_{z,ct}$$

$$SPILL_{z,ct} = \sum_{j \neq i} w^S_{jc,0} * K_{z,jt}$$

Aghion et al (2016)

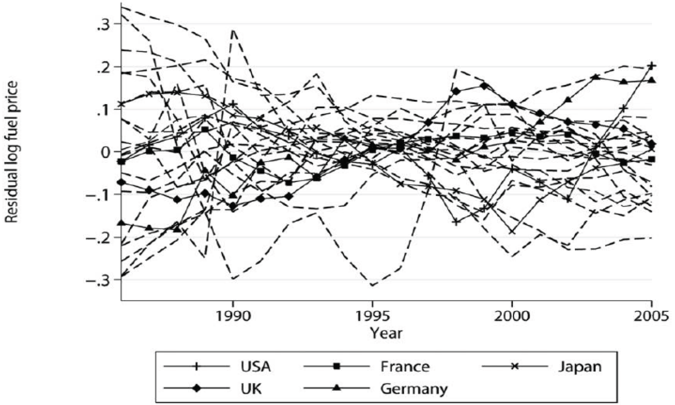


FIG. 3.—Residuals from a regression of country-level ln(fuel prices) on country and year dummies. This illustrates the variation that is driving the identification of price effects in our main regressions. The standard deviation of the residuals is 0.107.

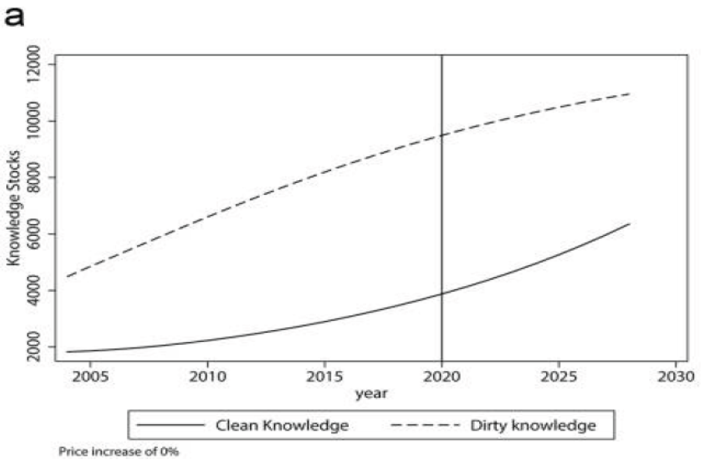
Aghion et al (2016)

Regressions of Clean and Dirty Patents

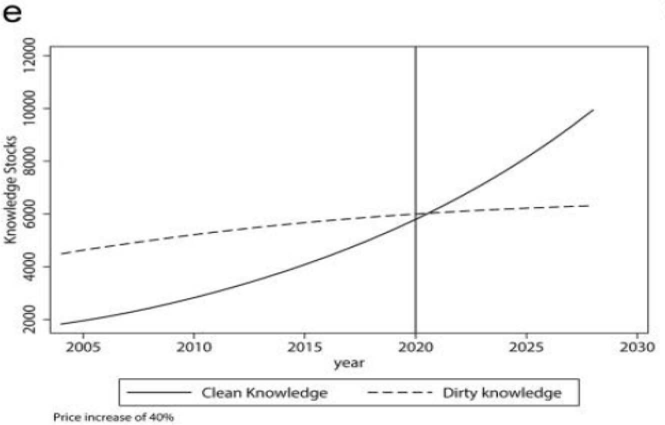
	Dependent Variable: Clean Patents			Dependent Variable: Dirty Patents		
	(1)	(2)	(3)	(4)	(5)	(6)
Fuel price (ln *FP*)	.970***	.962**	.843**	−.565***	−.553***	−.551***
	(.374)	(.379)	(.366)	(.146)	(.205)	(.194)
R&D subsidies (ln R&D)		−.005	−.006		−.006	−.005
		(.025)	(.024)		(.021)	(.020)
Emission regulation			−.008			.04
			(.149)			(.120)
Clean spillover (ln SPILL_C)	.268***	.301***	.266***	−.093*	−.078	−.089
	(.076)	(.087)	(.088)	(.048)	(.067)	(.063)
Dirty spillover (ln SPILL_D)	−.168**	−.207**	−.165*	.151**	.132	.138*
	(.085)	(.098)	(.098)	(.064)	(.082)	(.077)
Own stock clean (ln K_C)	.306***	.320***	.293***	−.002	−.004	.021
	(.026)	(.027)	(.025)	(.022)	(.022)	(.020)
Own stock dirty (ln K_D)	.139***	.135***	.138***	.557***	.549***	.539***
	(.017)	(.017)	(.017)	(.031)	(.022)	(.017)
Observations	68,240	68,240	68,240	68,240	68,240	68,240
Firms	3,412	3,412	3,412	3,412	3,412	3,412

Note.—Standard errors are clustered at the firm level. Estimation is by the CFX method. All regressions include controls for GDP per capita, year dummies, fixed effects, and three dummies for no clean knowledge, no dirty knowledge, and no dirty or clean knowledge (in the previous year). Fuel price is the tax-fuel price faced. R&D subsidies are public R&D expenditures in energy-efficient transportation. Emissions regulations are maximum levels of tailpipe emissions for pollutants from new automobiles.

Aghion et al (2016)



Aghion et al (2016)



Results from Aghion et al (2016)

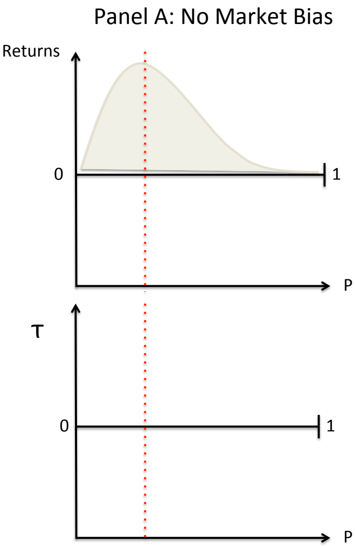
- 10% increase in fuel prices increase clean patenting by about 10%
- Patenting appears to be path dependent
- An increase of 40 percent of fuel prices with respect to the 2005 fuel price will allow clean innovation stocks to overtake dirty stocks after 15 years

Howell (2017)

Research Question: Do investment frictions slow development of energy efficiency products?

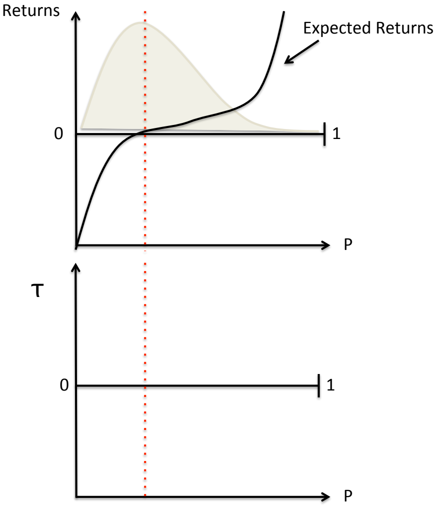
- Probably yes, but what are the magnitudes?
- If the answer is yes, then government could increase supply of energy efficiency products through addressing these frictions

Market Frictions and Outcomes



Market Frictions and Outcomes

Panel A: No Market Bias



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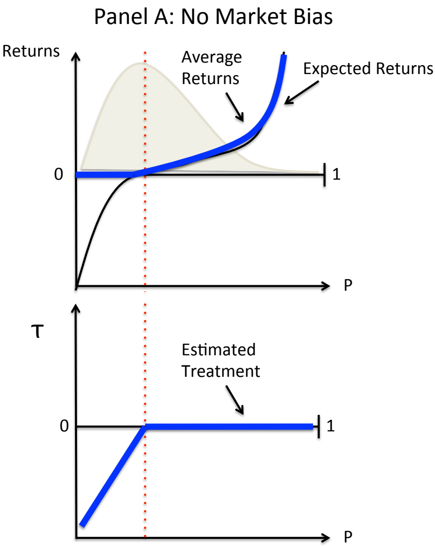

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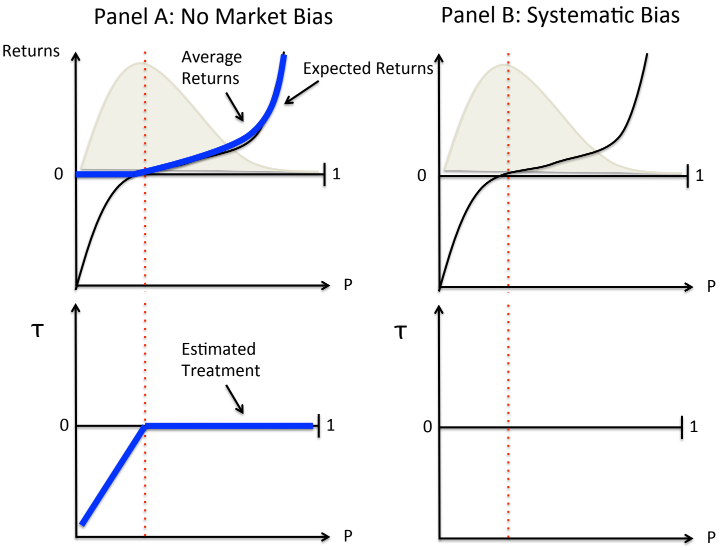

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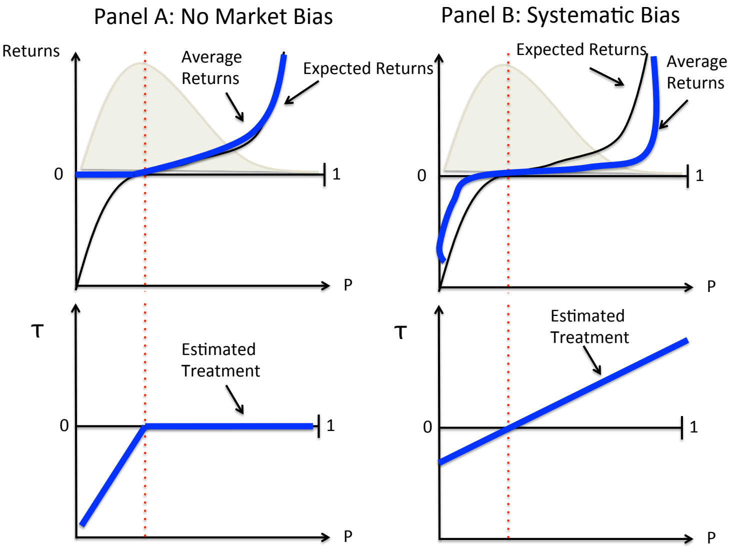


Key Question

- Does financing from outside private market lead to positive returns?
- If so, then the private market left gains “on the table”
- But how can we test this? Access to funding is going to be correlated with quality.

Howell (2017)

- US DOE grants for energy efficiency product development (1983 - 2007)
- Each grant is awarded as the result of a competition. Firms that barely won the competition vs barely lost should have the same underlying "quality" on average

Howell (2017)

Table 1—Summary Statistics

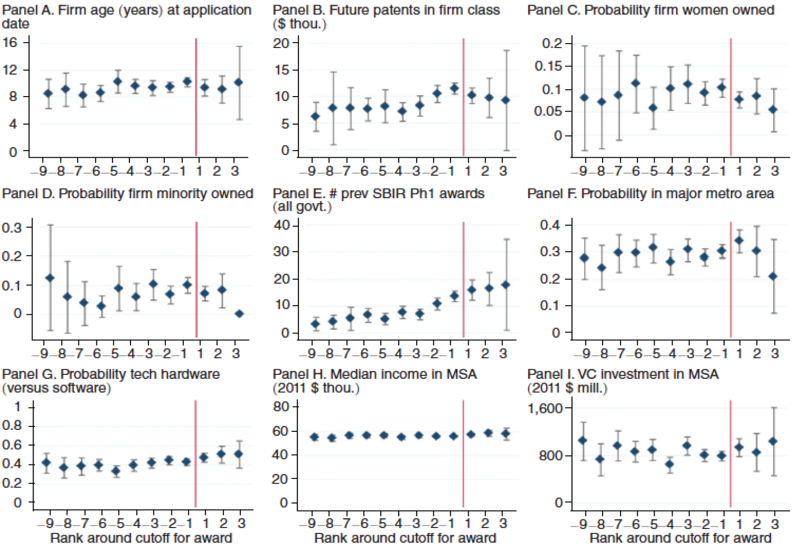
Panel A. Application data from DOE	
	1983–2013
Phase 1 applications	14,522
Unique Phase 1 applicant firms	7,419
Competitions	1,633

Howell (2017)

Panel B. Variables used in analysis from non-DOE sources

	Type	Mean	SD	Median	Observations
Pre-award venture capital (VC) investment	0–1	0.083	0.27	0	5,021
Pre-award venture capital deals	Count	0.25	1.3	0	5,021
Pre-award cite-weighted patents	Count	21	122	0	5,021
Pre-award patents	Count	1.9	7.5	0	5,021
Pre-award acquisition or IPO	0–1	0.033	0.18	0	5,021
Post-award VC $\left(VC_i^{post}\right)$	0–1	0.11	0.31	0	5,021
Post-award VC (mill 2012\$) $\left(VC\ Amt_i^{post}\right)$	Cont.	2.7	26	0	4,964
Post-award VC deals $\left(VC\ Deals_i^{post}\right)$	Count	0.32	1.4	0	5,021
Post-award cite-weighted patents $\left(Cites_i^{post}\right)$	Count	12	117	0	5,021
Post-award patents	Count	2	11	0	5,021
Post-award acquisition or IPO $\left(Exit_i^{post}\right)$	0–1	0.034	0.18	0	5,021
Revenue as of 2016 in \$ millions $\left(Revenue_i\right)$	Cont.	2.0	6.6	0.20	3,583
Survival as of 2016 $\left(InextrmBus_i^{post}\right)$	0–1	0.67	0.47	1	3,880
Probability in major metro area (top 6)	0–1	0.30	0.46	0	5,021
Age (years)	Count	9.5	11	6	3,427
Probability tech is hardware $\left(Hardware_i\right)$	0–1	0.43	0.49	1	2,571
Probability new subsector $\left(Emerging\ Sector_i\right)$	0–1	0.58	0.49	1	2,571
Probability minority owned	0–1	0.077	0.27	0	1,722
Probability woman owned	0–1	0.084	0.28	0	1,722
All-government SBIR wins $\left(SBIR_i\right)$	Count	10	36	0	5,021
Future patents in modal class	Count	9,758	11,809	5,453	1,583
MSA VC investment 2011 (\$millions)	Cont.	851	1,570	0	4,950
MSA median per cap. income 2011 (in \$thousands)	Cont.	56	14	56	4,603

Howell (2017)



Panel A. Firm age (years) at application date
Panel B. Future patents in firm class ($ thou.)
Panel C. Probability firm women owned
Panel D. Probability firm minority owned
Panel E. # prev SBIR Ph1 awards (all govt.)
Panel F. Probability in major metro area
Panel G. Probability tech hardware (versus software)
Panel H. Median income in MSA (2011 $ thou.)
Panel I. VC investment in MSA (2011 $ mill.)
Rank around cutoff for award

Howell (2017)

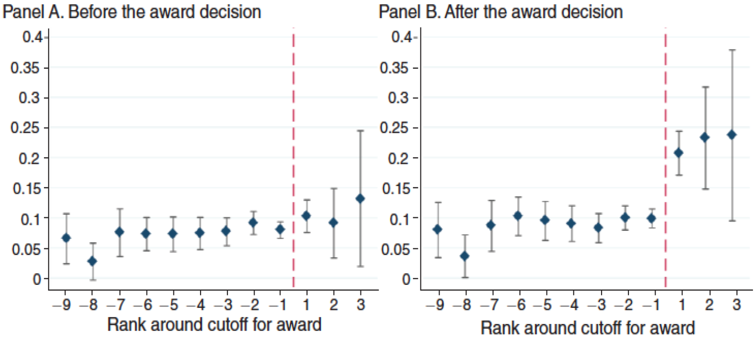


Figure 3. Probability of Venture Capital before and after Grant by Rank

Howell (2017)

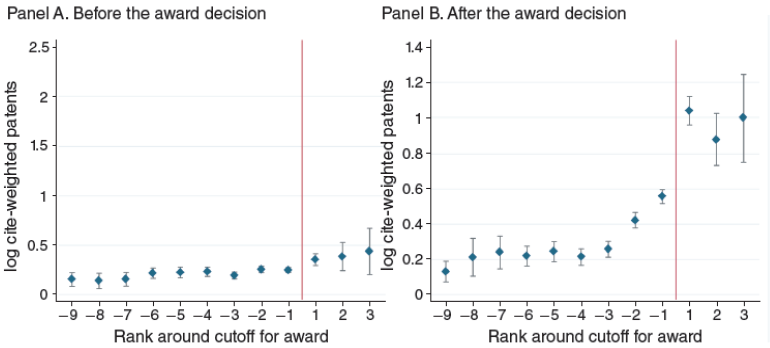


Figure 2. Cite-Weighted Patents before and after Phase 1 Grant by Rank

Howell (2017)

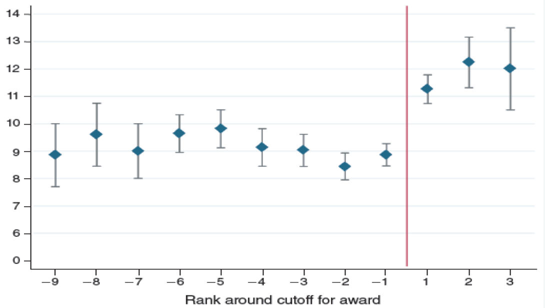


FIGURE 4. LOG REVENUE (*in $millions*)

Notes: This figure shows most recent year revenue as of January 2016 among post-2000 applicants. Out-of-business firms assigned zero revenue. Ninety-five percent confidence intervals shown.

Howell (2017)

TABLE 8—IMPACT OF PHASE 1 GRANT BY TECHNOLOGY (*Coefficient on award shown*)

	VC_i^{post} (1)	$\ln(1 + Cites_i^{post})$ (2)	$InBus_i^{post}$ (3)	Observations
Geothermal	0.56 (0.24)	−0.58 (0.30)	0.14 (0.13)	51
Hydropower, wave and tidal	0.51 (0.19)	0.50 (0.20)	0.26 (0.025)	236
Solar	0.25 (0.11)	0.15 (0.13)	0.20 (0.077)	421
Carbon capture and storage	0.20 (0.091)	0.73 (0.34)	0.25 (0.13)	211
Building and lighting efficiency	0.14 (0.057)	0.39 (0.16)	0.21 (0.048)	370
Vehicles, motors, engines, batteries	0.12 (0.060)	0.23 (0.12)	0.16 (0.059)	726
Wind	0.11 (0.039)	0.030 (0.10)	0.15 (0.093)	194
Advanced materials	0.11 (0.071)	−0.081 (0.18)	0.23 (0.077)	435
Biomass production/generation	0.085 (0.067)	0.036 (0.29)	0.21 (0.079)	308
Fuel cells and hydrogen	0.077 (0.072)	0.17 (0.18)	0.27 (0.10)	400
Natural gas	0.060 (0.074)	0.54 (0.45)	−0.15 (0.17)	255
Recycling, waste-to-energy, and water	0.045 (0.053)	0.094 (0.21)	0.061 (0.08)	549
Smart grid, sensors, converters	0.045 (0.053)	0.36 (0.21)	0.056 (0.069)	634
Air and emission control	0.025 (0.035)	0.20 (0.24)	0.20 (0.11)	300
Coal	0.024 (0.053)	0.79 (0.51)	0.11 (0.41)	108
Biofuels and biochemicals	0.014 (0.054)	0.036 (0.29)	0.051 (0.13)	176

Notes: This table reports regression estimates of the Phase 1 grant effect on VC investment, log cite-weighted patents, and survival by technology type using variants of equation (1). Each row represents a separate regression whose sample is limited to competitions in the technology type. Only the coefficient on treatment is shown. All models are OLS and use all the data. Other and Oil are omitted due to few observations. Standard errors robust and clustered at the sector-year level. Year $\geq$ 1995.

Howell (2017)

Grants increase

- Cite-weighted patents by 30%
- Chance of receiving VC funding by 9 percentage points
- Probability of generating positive revenue
- Revenue by 30%
- Probability of survival and exit

Summary

- Demand Side
    - Not very strong evidence to support investment frictions
    - $\Longrightarrow$ Subsidizing energy efficiency adoption is probably not a good policy
- Supply Side
    - Producers respond to energy prices.
    - And there appear to be investment frictions
    - $\Longrightarrow$ Subsidizing energy efficiency investment is probably good. Also, carbon/energy taxes are likely to induce more clean technology supply

References

- Howell, Sabrina T. "Financing innovation: evidence from R&D grants." The American Economic Review 107.4 (2017): 1136-1164.
- Aghion, Philippe, et al. "Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry." Journal of Political Economy 124.1 (2016): 1-51.
- Allcott, Hunt, and Michael Greenstone. "Is there an energy efficiency gap?." The Journal of Economic Perspectives 26.1 (2012): 3-28.