Efficiency & Innovation

Mohammad H. Rahmati

Sharif University Of Technology

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Table of Content

David, Fuchs, Gertler, “Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico”, AEJ:Policy (2014), Allcott, Knittel, Taubinsky. “Tagging and targeting of energy efficiency subsidies.”AER,(2015)

Davis, “Durable Goods and Residential Demand for Energy and Water: Evidence from a Field Trial”, RAND (2008)

Newell, Jaffe, Stavins, “ The Induced Innovation Hypothesis & Energy Saving Technological Change’ (1999), QJE,

Question

- Paper evaluates the impact and cost-effectiveness of a large-scale appliance replacement program in Mexico
- Between 2009 and 2012, Cash for Coolers (C4C) subsidize 1.9 million HH to replace their old refrigerators and air conditioners with newer, more energy-efficient models.
- Appliance had to be at least ten years old
- HH had to purchase an efficient appliance of same type.
- Old appliances recycle
- Refrigerator replacement reduces elec. cons. by 8 %
- Less than ex ante prediction by World Bank, McKinsey
- They predict four times larger than actual
- They predict larger savings from air conditioner replacement
- Findings show increases after households receive a new air conditioner.

Why Wrong Prediction

1. Optimistic to be able to recruit HH with very old, very inefficient appliances

   most of retired appliances were less than 12 years old
2. For air conditioners, is more usage due to less cost

   zero changes in electricity consumption during winter months, substantial increases in summer
3. Increases in appliance size and added features (side-by-side, ice-door) offset improvements in efficiency.

- Data features:
  - 25 million Mexican residential electricity billing (not self reported which are overstated)
  - large-scale national program (small-scale interventions: validity problem+ sample selection)

Context and Program Rationale

- CFE exclusive supplier of electricity within Mexico
- Electricity service in Mexico is highly reliable (one hour interruptions per year)
- Residential bill: no fixed, three tiers, subsidized
  - August 2011: tariff 1: 0.73 pesos (US$ 0.057) per kilowatt hour
  - Second US$ 0.096, third US$ 0.202 per kilowatt hour
  - in US: $0.117 (EIA 2013b)

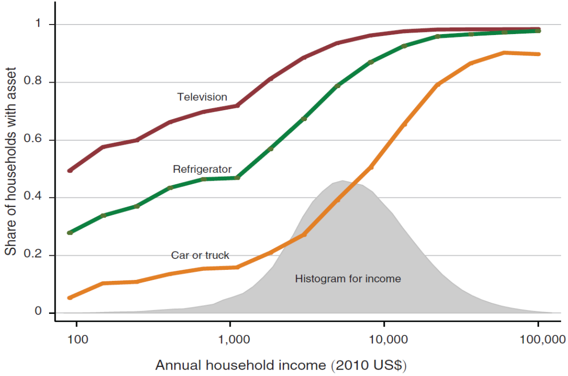
Demographics and Appliance Saturation in Mexico

- 97.5% have electricity, electricity consumption 1,900 kilowatt hours annually, (US 14,000)

	2000 census	2005 census	2010 census
Demographics:			
Total population (in millions)	97.0	102.8	112.0
Total number of households (in millions)	22.6	24.7	28.7
Household size (persons)	4.3	4.2	3.9
Household head completed high school	26.8%	29.6%	32.1%
Number of rooms in home	4.32	4.19	4.58
Improved flooring	86.0%	89.2%	93.9%
Electricity and appliance saturation:			
Electricity in the home	94.7%	96.4%	97.5%
Refrigerator	68.2%	79.1%	82.5%
Washing machine	51.6%	63.0%	67.0%
Television	85.6%	90.9%	92.6%
Computer	9.2%	19.9%	30.0%

- Driver of high demand growth: increase in appliance ownership

Durable Good Ownership Rates by Income Level in Mexico



- Require massive investment in infrastructure
- Program goal to reduce investment

Program Details

- Objective: reduce electricity consumption
- Geographic requirement for air conditioner: live in a warm climate zone. (excluded 75 % hh)
- No geographic restrictions for refrigerator replacement
- Direct cash payments in three amounts$30, $110, and $170
- Retailers charge $30 for delivering
- Eligibility for these different payment levels depended on a household's average historical electricity consumption.
- Very low historic consumption: ineligible for program
- If eligible, more historic consumption reduce transfer
- To avoid large cash payments to high-income households
- Three-quarters of participants qualified for $170
- Moreover, program offered on-bill financing at a 14% annual interest rate, repaid over four years

Program Details

- Program represented a substantial incentive for replacement
- Participants paid $427 per refrigerator, $406 per air conditioner
- Received subsidies immediately
- 90% of all replacements were refrigerators
- Because of geographic restrictions+ uncommon air conditioning

Data and Empirical Framework

- Two datasets: 12 month panel bills + C4C participants
- No data on other forms of energy use (HH able to substitute between electricity, natural gas)
- Much less substitute because of air conditioning+refrigerator
- Difference-in-differences: comparing electricity consumption before and after appliance replacement

$$y_{it} = \beta_1 1[NewRef.]_{it} + \beta_2 1[NewAirCond.]_{it} + \gamma_{i,moy} + \omega_t + \varepsilon_{it}$$

- Equal to 1 for C4C participants after replacement
- β_1 and β_2 measure mean change in electricity consumption associated with appliance replacement.
- $\gamma_{i,moy}$ month-of-year fixed effects $\Rightarrow$ each household 12 separate fixed effects, one for each calendar month
- Controls time-invariant HH + HH-specific seasonal variation

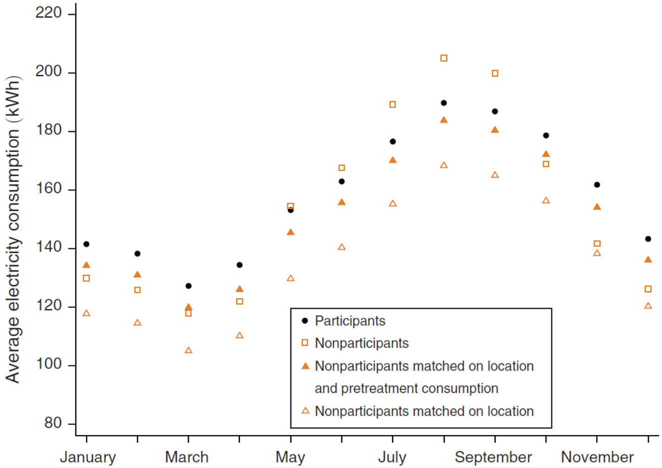
Empirical Strategy

- Billing data includes identifiers house and household
- Observe when a new household moves into
- Expect participation correlated with decision to move
- Month-of-sample fixed effects ω_t controls for month-to-month differences in weather
- Cluster standard errors at county to allow for arbitrary serial correlation and correlation across households within counties.
- Concern: Replacement may systematically coincide with other events (new baby, new job)

Comparison Groups

- Different comparison groups
  - Equal-sized random sample of nonparticipating households
  - A sample that includes participating households only (control is those not replaced yet)
  - Using matched based
    1. purely on location: closest consecutive nonparticipating account number (experiencing same weather)
    2. on both location and pretreatment electricity consumption: select ten nonparticipating households with the closest account numbers, then select the closest consumption
- Figures plot three comparison groups.

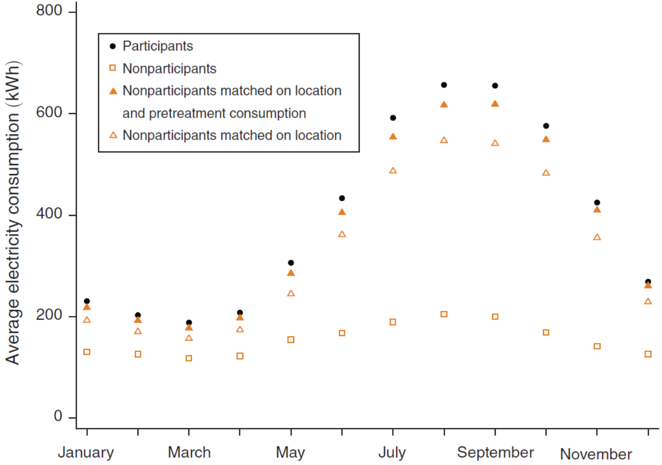
Comparing Participants to Nonparticipants: Refrigerators



Comparison Groups

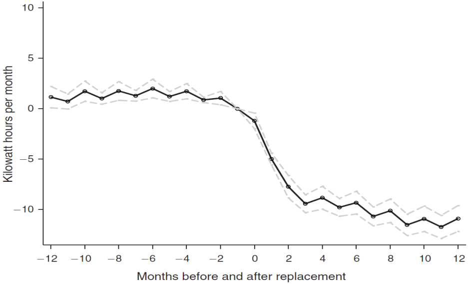
- For refrigerator all comparisons seems good
- For air conditioners, nonparticipants do not appear to be a good comparison group, probably had no air conditioning
- Households are self-selecting into the C4C program, different from nonparticipating households
- Nonexperimental data
- Best seems matched based on consumption + location

Comparing Participants to Nonpartic.: Air Conditioners



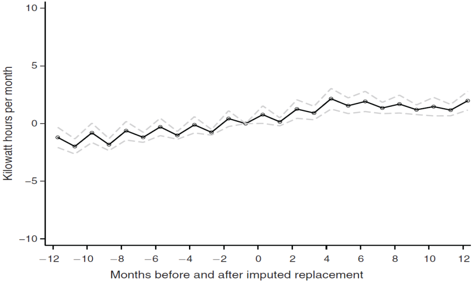
Graphical Results

- Focus on refrigerators: 90% of replacement+less seasonal
- Plot α from $y_{it} = \sum_{k=-12}^{12} \alpha_k 1[\tau_{it} = k]_{it} + \gamma_i + \omega_{ct} + \varepsilon_{it}$
- τ event month $\tau = 0$ for exact month of replacement
- ω_{ct} county-month FE
- Sample: participate+matched location and pretreatment consumption, in equal number



Graphical Results

- Notice the bill are bi-monthly, so drop take place in couple month (measurement error)
- Next, same exercise but assigning event study indicators to the comparison group, rather than the treatment group
- Replacement date of their match.



- Probably need parametric time trends in regressions.

Baseline Estimates

- Columns 1–3 are complete set of participating households and an equal-sized random sample of nonparticipating households
- Refrigerator replacement decreases electricity consumption by between 10.3-12.4 kilowatt hours per month (8% decrease)
- Air conditioning insignificantly increases consumption
- Interaction between air conditioning replacement and six summer months (May–October)
- Replacement may have larger impact during warm weather.
- Increase in summer consumption
- Columns 4-5 estimate regressions using only participating households.

Appliance Replacement on Household Electricity Consumption

	(1)	(2)	(3)	(4)	(5)
$1[\textit{New refrigerator}]_{it}$	−12.4**	−10.3**	−10.3**	−11.4**	−11.9**
	(1.4)	(0.6)	(0.6)	(0.7)	(0.75)
$1[\textit{New air conditioner}]_{it}$	6.6	7.2*	1.4	1.4	1.2
	(5.6)	(3.2)	(1.1)	(1.2)	(1.3)
$1[\textit{New air conditioner}]_{it} \times 1[\textit{Summer months}]_{it}$			14.3*	12.1*	13.6*
			(6.0)	(5.9)	(6.2)
Household by calendar month fixed effects	Yes	Yes	Yes	Yes	Yes
Month-of-sample fixed effects	Yes	Yes	Yes	Yes	Yes
Month-of-sample by county fixed effects	No	Yes	Yes	Yes	Yes
Including treatment households only	No	No	No	Yes	Yes
Dropping month of replacement	No	No	No	No	Yes
Number of households	1,914,160	1,914,160	1,914,160	957,080	957,080
R^2	0.91	0.91	0.91	0.93	0.93

Matching Estimates

- Matching identical to columns 1–3 of previous table.
- Very similar results
- Time trend: for participating households, is equal to the number of months since May 2009, and for nonparticipating households is equal to zero for all months.
- Time trend: linear, quadratic, cubic

Appliance Replacement on Household Electricity Consumption: Matching Estimates

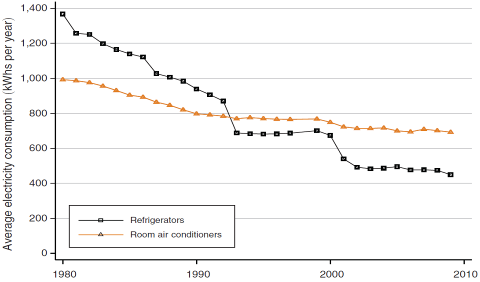
	Matching on location			Matching on location and pretreatment consumption		
	(1)	(2)	(3)	(4)	(5)	(6)
$1[New\ refrigerator]_{it}$	−11.0**	−10.9**	−10.9**	−9.5**	−9.2**	−9.2**
	(0.7)	(0.5)	(0.5)	(0.7)	(0.5)	(0.5)
$1[New\ air\ conditioner]_{it}$	8.0	6.5*	0.1	9.5	8.3**	2.1*
	(5.3)	(3.2)	(1.2)	(5.2)	(3.0)	(1.0)
$1[New\ air\ conditioner]_{it} \times 1[Summer\ months]_{it}$			15.5*			15.2*
			(6.3)			(6.1)
Household by calendar month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Month-of-sample fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Month-of-sample by county fixed effects	No	Yes	Yes	No	Yes	Yes
Number of households	1,914,160	1,914,160	1,914,160	1,914,160	1,914,160	1,914,160
R^2	0.93	0.93	0.93	0.92	0.92	0.92

Appliance Replacement on Household Electricity Consumption: Including Time Trends

	No time trend (1)	Linear time trend (2)	Quadratic time trend (3)	Cubic time trend (4)
$1[\textit{New refrigerator}]_{it}$	−9.2**	−11.2**	−11.2**	−11.2**
	(0.5)	(0.7)	(0.7)	(0.7)
$1[\textit{New air conditioner}]_{it}$	2.1*	0.1	0.3	0.2
	(1.0)	(1.0)	(1.0)	(1.0)
$1[\textit{New air conditioner}]_{it} \times 1[\textit{Summer months}]_{it}$	15.2*	15.3*	15.0*	15.0*
	(6.1)	(6.1)	(6.1)	(6.1)
Household by calendar month fixed effects	Yes	Yes	Yes	Yes
Month-of-sample by county fixed effects	Yes	Yes	Yes	Yes
Number of households	1,914,160	1,914,160	1,914,160	1,914,160
R^2	0.92	0.92	0.92	0.92

Mechanisms-Appliance Age

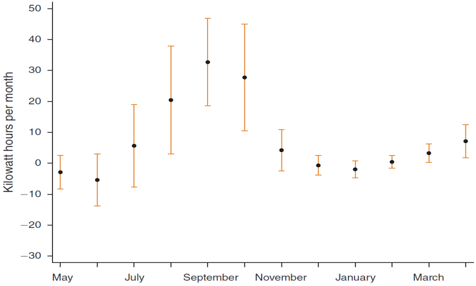
- Sales-weighted electricity consumption for refrigerators



- Minimum energy-efficiency standards in 1990, 2001
- Average age of replacement 13.5 years.
- To justify 481 kilowatt hours per year by World Bank (real 135) need replacement of over 20+ years

Mechanisms-Appliance Usage

- Increases in new air conditioners usage because cost less
- Leave usage of fan
- Effect of air conditioner replacement



- Zero during winter, but large + positive during summer
- Increase in consumption also induced by more capacity and features.

Appliance Size and Features

- Under the program's rules, specific size requirements.
  - New refrigerators were supposed to be between 9 and 13 cubic feet, and have a maximum size no more than two cubic feet larger than the refrigerator which is replaced.
- Many of the appliances for sale in Mexico during this period exceeded these requirements.
- Each additional cubic foot of refrigerator
- More importantly, new appliances: ice-makers, side-by-side doors,
- Energy-intensive appliance

Possible Nonworking Appliances

- Appliances were supposed to be in working order to be eligible for replacement
- If able to replace by nonworking, explain gap between estimates and ex ante predictions
- Retailer has incentive to approve appliances
- Appliance tested again in recycling center, so risky for him to deviate.

Heterogeneous Effects

- By income:
  - largest decreases are observed in high-income counties
  - they had larger and more feature-rich refrigerators pre-substitution
- By age of old appliance
  - no evidence of larger savings for households who replace older appliances.
  - Mis-measurement in self reported data
- By the year of replacement
  - Savings tend to decrease over time
  - households with very old or very energy-inefficient appliances would have likely wanted to participate in C4C as soon as possible

Heterogeneous Effects

	Refrigerators	Air conditioners
Panel A. By mean household income in county (2010 census)		
First tercile (less than $5,000/year)	−6.7** (0.3) N = 305,669	5.4* (2.9) N = 13,202
Second tercile ($5,000–$7,637/year)	−10.0** (1.1) N = 275,941	7.6** (1.8) N = 42,176
Third tercile (more than $7,637/year)	−11.0** (0.9) N = 277,352	9.5 (6.5) N = 43,226
Panel B. By age of old appliance (self-reported)		
Old appliance exactly 10 years old	−9.2** (0.6) N = 380,803	8.9* (3.5) N = 66,964
Old appliance 11–14 years old	−9.1** (0.7) N = 214,940	6.8** (2.7) N = 23,753
Old appliance 15+ years old	−9.3** (0.5) N = 263,219	7.3* (3.1) N = 7,887
Panel C. By year of replacement		
Appliance replaced in 2009	−9.7** (0.7) N = 180,507	6.4 (5.0) N = 15,267
Appliance replaced in 2010	−9.5** (0.6) N = 497,148	8.3** (3.1) N = 59,499
Appliance replaced in 2011	−3.2** (0.4)	11.7** (2.5)

Cost Effectiveness

- Refrigerator replacement saves $13 annually, air conditioner costs $9
- Total impact: 106.7 gigawatt hours, $10 million annually
- Decrease of 57,400 tons of carbon dioxide emissions annually
- CO_2 social cost $34 per ton $\Rightarrow$ $2.0 million in benefits
- Benefit of reduce SO_2 $2.9 million annually.
- Ignore energy used to produce new product and recycling
- Program costs $129 million for refrigerators, $13 million for air conditioners.
- Ignore program design, administration, advertising $\cdots$ costs
- 5 % annual discount rate
- Program cost per kilowatt hour is $0.29 , very high

Cost Effectiveness

	Refrigerators (1)	Air conditioners (2)	Both appliances combined (3)
Panel A. Mean per replacement			
Mean annual change in electricity consumption per replacement (kilowatt hours)	−135	91	—
Mean annual change in household expenditure per replacement (2010 US$)	−$13	$9	—
Panel B. Totals			
Total replacements nationwide (between May 2009 and April 2011)	858,962	98,604	957,566
Total annual change in electricity consumption (gigawatt hours)	−115.7	9.0	−106.7
Total annual change in household expenditures (in millions 2010 US$)	−$11.1	$0.9	−$10.2
Total annual change in carbon dioxide emissions (thousands of tons)	−62.2	4.8	−57.4
Panel C. Cost-effectiveness			
Total Direct program cost (in millions 2010 US$)	$129.4	$13.4	$142.7
Program cost per kilowatt hour (2010 US$)	$0.25	—	$0.29
Program cost per ton of carbon dioxide (2010 US$)	$457	—	$547

Welfare

- Difference between marginal and inframarginal HH who are getting paid to do what they would have done otherwise.
- Cost-effectiveness assume that all households are marginal
- Overstating the environmental benefits of the program
- Inframarginal value \$1 in subsidy at exactly \$1, so pure transfer
- Marginal otherwise stayed with their old energy-inefficient durable good
- Collecting tax is welfare loss
- Welfare losses (\$140 M.) must be compared to welfare gains from decreased externalities (\$2M. +\$2.9M)
- Costs of the program exceeded the benefits.

Question and Motivation

- Corrective taxation to address distortions: externalities, internalities
- Distortions heterogeneous
  - some cars pollute more
  - some over-consume alcohol
- Question: whether a corrective tax is "well-targeted"?
- Does it primarily affect individuals subject to relatively large distortions?
- Could reduce welfare if target undistorted decisions.

Introduction

- This paper studies the targeting of corrective subsidies for energy efficient durable goods such as air conditioners, insulation, and cars.
- Because of environmental externalities, credit constraints, "landlord-tenant", information asymmetries, imperfect information, and "behavioral" (inattention to energy costs)
- Show distortions are heterogeneous
  - wealthy are less credit constrained
  - homeowners unaffected by "landlord-tenant" problem
  - environmentalists attentive to energy costs
- Results: efficiency subsidies are adopted by people that less affected by distortions: wealthy environmentalist homeowners

A Model of Optimal Subsidies and Targeting

- A unit mass of consumers binary choice: but efficient or not
- Constant marginal cost c competitive market
- Subsidy s , price $p = c - s$
- Social value of purchasing v
- Private valuations $\hat{v} = v - d$
- D from "distortion"
- Positive (negative) d means distorted away from (toward) energy efficient good
- Two distortion types $j \in \{L, H\}$, with population shares α_j and distortions $d_L < d_H$
- Consumers purchase the good if and only if $\hat{v} > p$

A Model of Optimal Subsidies and Targeting

- Z denotes consumers' initial wealth
- F_j denotes type j's CDF of $\hat{v}$, differentiable
- $Q_j(p)$: share of type j consumers who purchase
- $D(p) = \alpha_L Q_L(p) + \alpha_H Q_H(p)$ total demand
- Social planner maximizes
  $W(s) = Z - R(s) + \sum_j \alpha_j \int_{x \geq c-s} (x + d_j - p) dF_j(x)$
- $R(s)$ is a lump-sum transfer that funds the subsidy

Implications of a Poorly-Targeted Subsidy

- Let $\bar{d} = \sum \alpha_j d_j$
- "targeting": whether high-distortion types are more responsive to the subsidy: $\tau(s) \equiv cov(d_j, -Q'_j(c-s))$
- Well-targeted (poorly-targeted) if $\tau(s)$ is high (low).
- Welfare impact of a marginal increase in subsidy

$$W'(s) = (s - \bar{d})D'(c-s) + \tau(s)$$

- Poorly-targeted subsidy generates lower welfare gains than a well-targeted subsidy.
- F.o.c $s^* = \bar{d} - \frac{\tau(s)}{D'(c-s)}$
- Because $D' < 0$ optimal subsidy is increasing in $\tau(s)$

Tagging Is More Valuable With Poor Targeting

- Tagging(Akerlof 1978): limiting eligibility to individuals subject to greater distortions
- Tag' using type-specific subsidies s_L and s_H
- ΔW welfare gains from optimal type-specific subsidies relative to optimal uniform subsidy.
- $s_L^* = d_L$ and $s_H^* = d_H$
- More heterogeneity in d_j implies that s_L^* and s_H^* deviate more from s^*
- Implies larger ΔW
- Proposition 1: If $Q_L''(p), Q_H''(p) \approx 0$ for $p \in [c - s_H^*, c - s_L^*]$, then ΔW is increasing in $|\tau(s)|$
- Intuitively, ΔW is smallest when $s^* = \bar{d}$, which occurs when $\tau(s)$ is zero.

Distortions Are Heterogeneous on Observables

- Whether environmentalists have different factual beliefs about the financial savings from energy efficient goods

Dependent variable	CFL savings belief (1)	Energy Star savings belief (2)	MPG savings belief (3)	Fuel cost calculation effort (4)
Environmentalist	7.81	21.04	−2.70	0.193
	(3.08)**	(4.80)***	(3.24)	(0.112)*
Observations	1,475	799	1,392	1,483
Dataset	Lightbulbs	Water heaters	VOAS	VOAS

- Environmentalist is a self-reported level in surveys
- Environmentalists higher in perceived financial savings
  - 7.8 %fluorescent lightbulbs
  - 21 % Energy Star water heaters
  - Not statistically different beliefs about higher-MPG vehicle
  - Have lower d ,

Characteristics of Energy Efficiency Subsidy Adopters

- Next Table: participation at a large utility in energy efficiency program
- Dependent: whether household claimed a utility-provided subsidy for energy efficient appliances
- Subsidy recipients are wealthier, poorly targeted to address credit constraints
- Take-up is much lower at rental homes: poorly targeted toward "landlord-tenant" information asymmetries
- More likely to have solar energy systems or green pricing program $\Rightarrow$ target environmentalists

Correlates of Energy Efficiency Subsidy Take-Up

Dependent variable	1(Take up utility subsidy) (1)	1(Take up tax credit) (2)	1(Own hybrid) (3)	Subsidy awareness (4)
1(Green pricing participant)	0.015			
	(0.004)***			
1(Installed solar system)	0.892			
	(0.002)***			
Income ($ millions)	0.543	0.505	0.278	1.022
	(0.066)***	(0.152)***	(0.136)**	(0.720)
1(Rent)	−0.068			−0.084
	(0.007)***			(0.081)
Environmentalist		0.121	0.020	0.248
		(0.024)***	(0.008)**	(0.116)**
Fuel cost calculation effort		0.027	0.017	
		(0.011)**	(0.007)**	
Observations	75,591	2,982	1,483	1,516
Dataset	Utility	All TESS	VOAS	Lightbulbs
Dependent variable mean	0.109	0.102	0.013	0

Characteristics of Energy Efficiency Subsidy Adopters

- Column 2: federal Residential Energy Credits, which provide income tax credits for home energy efficiency investments.
- Column 3: hybrid vehicle ownership, (heavily subsidized)
- Again adopters wealthier and environmentalist.
- Positive fuel cost calculation effort: more attentive guy more likely to take up
- Column 4: question: whether energy efficiency rebates or loans are available in their area
- Exist every where but people unaware
- Environmentalists are 0.248 standard deviations more aware
- Caveat: above study average, not marginal consumers
- Equivalent if no consumer would purchase the energy efficient good without the subsidy $D(c) = 0$
- Assumption is tenuous, but they can do nothing!!

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Introduction

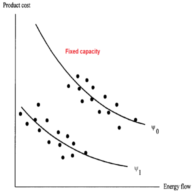
- Newell, Jaffe, Stavins, " The Induced Innovation Hypothesis & Energy Saving Technological Change' (1999), QJE
- Theory: price of energy rises, $\Rightarrow$ fall in energy intensity
  - behavioral changes (drive less)
  - invention of more efficient car: "induced innovation"
- Hicks: "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive [1932, pp. 124–125]."
- Literature: inducement in aggregate production function: technological change (new cars) $\Rightarrow$ test product characteristics

Introduction

- Schumpeter [1939]:
  - "invention": creating a new technological possibility
  - "innovation": commercial introduction of a new technical idea
  - "diffusion": gradual adoption by firms or individuals of commercially available products.
- This paper: inducement: characteristic "energy efficiency" of items on capital goods menu (air conditioning, heaters) should improve faster than it otherwise would.

Characteristics Transformation Sources

- A product w/ dimensionality $n+1$, n : # of product attributes or characteristics
- Cost of production a model: additional characteristic
- Example: Air conditioner w/ two characteristics:
  - energy flow per unit of time f
  - cooling capacity c
- k: cost of producing a model i with a bundle of chr
- Transformation surface: $ln(k_i) = \alpha + \beta_1 ln(f_i) + \beta_2 ln(c_i)$



Characteristics Transformation Source

- ψ_0 & ψ_1 for times t_0 & t_1
- Suppose: price of energy increased between t_0 & t_1
  1. Frontier moved toward the origin ⇒ cheaper & more energy efficient
  2. Slope of frontier decreased ⇒ elasticity of product cost w.r.t. energy flow is lower (trade-off s.t. energy efficiency is less expensive on the margin)
  3. Models shifted toward less energy-intensive models
- Decompose energy efficiency
  1. overall technological change
  2. directional technological change
  3. model substitution
- (1) & (2): changes in parameters of transformation surface
- (3) model substitution "movements along" this surface

Econometric Specification

- Separately estimate for room air conditioners, central air conditioners, and gas water heaters,

$$ln(k_{it}) = \alpha + \beta_2 ln(f_{it}) + \beta_2 ln(c_{it}) + \beta_3 2speed + \beta_4 3speed + \varepsilon_{it}$$

$$ln(k_{it}) = \alpha + \beta_1 ln(f_{it}) + \beta_2 ln(c_{it}) + \varepsilon_{it}$$

$$ln(k_{it}) = \alpha + \beta_1 ln(f_{it}) + \beta_2 ln(c_{it}) + \beta_5 ln(g_{it}) + \varepsilon_{it}$$

- c is cooling or heating capacity, $2speed$ & $3speed$ dummy for $\#$ of fan speed air conditioners, g storage capability in gas water heaters, i indexes product models, t time
- Simplified notation by omitting product-specific subscripts on α, β, γ (not equal across products)
- Parameters can vary by relative price of energy p & level of energy efficiency standards s

Econometric Specification

- Later they show: "overall" improvements by α "directional" technological change by β
- Price induce which technological change (α & β?
- Varying coefficients

$$\alpha = \alpha_0 + \alpha_1 t + \alpha_3 ln(q_t) + \alpha_4 ln(p_{t-j}) + \alpha_5 s$$

$$\beta_1 = \beta_{10} + \beta_{11} t + \beta_{12} t^2 + \beta_{13} ln(p_{t-j}) + \beta_{14} s$$

$$\beta_2 = \beta_{20} + \beta_{21} t + \beta_{22} t^2$$

- t time, p relative price of energy, s level of energy efficiency standards, q aggregate product shipments.
- $j = 3$ years
- Again, α & β not required to be equal across products

Data

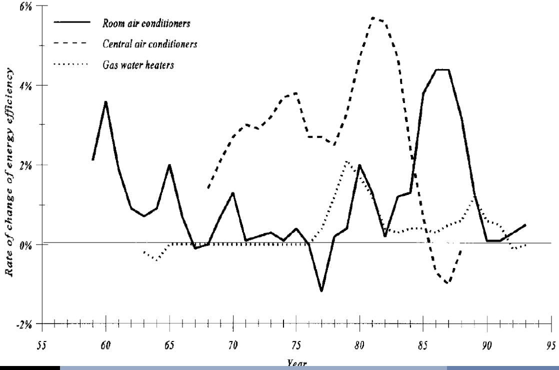
- Public data sources: chr+prices
  - 735 room air conditioner b/w 1958-1993
  - 275 central air conditioner models b/w 1967-1988
  - 415 gas water heater models from 1962-1993

Summary Statistics for Variables

Variable	Symbol	Overall Mean	Overall Std dev	Initial year Mean	Initial year Std dev	Final year Mean	Final year Std dev	Mean growth rate
Room air conditioners (1958–1993; N = 735)								
Energy flow (1000 watt)	f	1.5	1.0	1.9	0.6	1.2	0.8	−1.3%
Energy efficiency (Btu/hr/watt)	e	7.6	1.4	5.9	1.0	9.0	0.6	1.2%
Cooling capacity (1000 Btu/hr)	c	11.4	6.7	10.8	3.1	10.6	6.2	−0.1%
Nominal price ($)		376	166	248	64	548	166	2.3%
Product cost (overall normalized mean = 1)	k	1.00	0.46	1.85	0.47	0.86	0.26	−2.2%
Shipments (millions/year)	q	3.39	1.21	1.67	—	3.08	—	1.8%
Relative price of electricity (1975 = 1)	p_f	1.08	0.10	1.25	—	1.14	—	−0.3%
Central air conditioners (1967–1988; N = 275)								
Energy flow (1000 watt)	f	4.4	1.5	6.1	1.8	3.5	1.4	−2.6%
Energy efficiency (Btu/hr/watt)	e	8.3	1.7	6.4	0.1	10.8	0.4	2.5%
Cooling capacity (1000 Btu/hr)	c	35.1	10.0	39.3	12.1	37.2	14.0	−0.3%
Nominal price ($)		911	404	531	158	1299	313	4.4%
Product cost (overall normalized mean = 1)	k	1.00	0.26	1.23	0.37	0.85	0.21	−1.8%
Shipments (millions/year)	q	2.66	0.91	1.01	—	4.35	—	7.2%
Relative price of electricity (1975 = 1)	p_f	1.04	0.10	1.02	—	1.11	—	0.3%
Gas water heaters (1962–1993; N = 415)								
Energy flow (1000 Btu)	f	44.1	12.2	47.0	12.0	40.0	7.7	−0.5%
Energy efficiency (90° gal/1000 Btu)	e	0.98	0.05	0.94	0.03	1.05	0.05	0.3%
Heating capacity (90° gal/hr)	c	43.0	11.0	44.4	11.6	42.0	8.5	−0.2%
Storage capability (gallons)	g	41.8	11.1	36.3	7.4	46.8	14.0	0.8%
Nominal price ($)		173	96	79	21	284	104	4.2%
Product cost (overall normal-								

Changes in Energy Efficiency

- Annualized rates of change in energy efficiency
  - central air conditioners: 2.6%
  - room air conditioners: 1.2%
  - gas water heaters: 0.3%

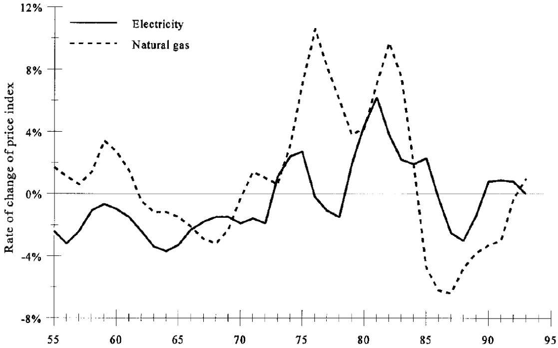


Cost/Price Data

- No data on costs
- Use price as a proxy for model's product cost
- Assumption: price/cost markup constant across models and time for a particular product
- Deflate to get real price

Relative Price of Energy

- Hypothesis: inducement is driven by price of energy relative to price of product inputs
- Energy: electricity + (air conditioners) & natural gas (water heaters)



Energy Efficiency Standards

- National Appliance Energy Conservation Act of 1987 (NAECA)
- Mandated minimum energy efficiency standards
  - room air conditioners and gas water heaters after January 1, 1990
  - central air conditioners after January 1, 1992
- Manufacturers did not wait until the deadline to meet the standards
- Dummy for years between act and enactment

Characteristics Transformation Surfaces

- "pure" autonomous technological change: no p (energy price) or s (regulation year dummies)
- induced innovation model (last two columns)
- Coefficient on time is negative in all cases
- Cost of durable goods increases with increasing energy efficiency, capacity,
- $ln(f)$: β_{10} measures elasticity of product cost w.r.t energy flow, negative: reductions in energy flow with higher product cost
- α_1 signf -: autonomous overall technological change
- Autonomous "directional" change: changes over time in the slope of the transformation surface
- Little evidence of significant inducement effects on overall technological change
- Energy-price induced changes in the slope (β_{13}) statistically

Transformation Surface Estimates: Room Air Conditioners

Parameter	Explanatory variable	Autonomous innovation	Induced innovation: Specification 1	Induced innovation: Specification 2
β_{10}	$\ln f$	−0.387	−0.362	−0.383
		(0.027)	(0.026)	(0.026)
β_{11}	$t \ln f$	0.80e-3	1.17e-3	1.51e-3
		(2.68e-3)	(2.88e-3)	(2.94e-3)
β_{12}	$t^2 \ln f$	8.33e-4	0.70e-4	3.28e-4
		(2.42e-4)	(3.14e-4)	(2.98e-4)
β_{13}	$\ln p \ln f$	—	0.410	0.361
			(0.125)	(0.127)
β_{14}	$s \ln f$	—	0.028	0.034
			(0.011)	(0.012)
β_{20}	$\ln c$	0.919	0.914	0.937
		(0.028)	(0.027)	(0.027)
β_{21}	$t \ln c$	−2.73e-3	−1.04e-3	−1.16e-3
		(2.95e-3)	(3.05e-3)	(3.10e-3)
β_{22}	$t^2 \ln c$	−6.78e-4	−5.90e-4	−8.69e-4
		(2.68e-4)	(2.93e-4)	(2.75e-4)
β_3	*2speed*	0.197	0.202	0.201
		(0.016)	(0.016)	(0.016)
β_4	*3speed*	0.300	0.299	0.298
		(0.016)	(0.016)	(0.016)
α_0	*constant*	−0.215	−0.234	−0.220
		(0.017)	(0.019)	(0.016)
α_1	t	−0.026	−0.026	−0.027
		(0.001)	(0.001)	(0.001)
α_2	t^2	1.05e-3	1.05e-3	0.93e-3
		(0.19e-3)	(0.19e-3)	(0.06e-3)
α_3	$\ln q$	−0.083	−0.083	−0.102
		(0.024)	(0.024)	(0.016)

Transformation Surface Estimates: Central Air Conditioners

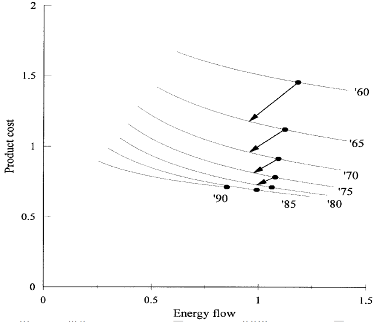
Parameter	Explanatory variable	Autonomous innovation	Induced innovation Specification 1	Induced innovation Specification 2
β_{10}	$\ln f$	−1.247	−1.205	−1.177
		(0.077)	(0.087)	(0.082)
β_{11}	$t \ln f$	−0.103	−0.107	−0.103
		(0.014)	(0.016)	(0.014)
β_{12}	$t^2 \ln f$	4.87e-3	4.04e-3	2.81e-3
		(1.41e-3)	(2.14e-3)	(1.67e-3)
β_{13}	$\ln p \ln f$	—	0.968	1.291
			(0.566)	(0.558)
β_{20}	$\ln c$	1.978	1.991	1.978
		(0.079)	(0.083)	(0.078)
β_{21}	$t \ln c$	0.101	0.107	0.105
		(0.013)	(0.015)	(0.014)
β_{22}	$t^2 \ln c$	−4.43e-3	−5.26e-3	−4.60e-3
		(1.41e-3)	(1.80e-3)	(1.42e-3)
α_0	*constant*	0.086	0.064	0.086
		(0.010)	(0.018)	(0.010)
α_1	t	−0.051	−0.055	−0.052
		(0.004)	(0.005)	(0.004)
α_2	t^2	−1.48e-3	−0.64e-3	−1.49e-3

Transformation Surface Estimates: Gas Water Heaters

Parameter	Explanatory variable	Autonomous innovation	Induced innovation: Specification 1	Induced innovation: Specification 2
β_{10}	$\ln f$	−3.918	−3.829	−3.925
		(0.235)	(0.267)	(0.221)
β_{11}	$t \ln f$	−0.055	−0.074	−0.061
		(0.032)	(0.023)	(0.028)
β_{12}	$t^2 \ln f$	0.012	0.013	0.013
		(0.002)	(0.002)	(0.002)
β_{13}	$\ln p \ln f$	—	−0.056	−0.088
			(0.263)	(0.227)
β_{14}	$s \ln f$	—	−0.079	−0.032
			(0.058)	(0.051)
β_{20}	$\ln c$	4.670	4.557	4.659
		(0.238)	(0.271)	(0.226)
β_{21}	$t \ln c$	0.071	0.094	0.077
		(0.032)	(0.023)	(0.028)
β_{22}	$t^2 \ln c$	−0.011	−0.012	−0.011
		(0.002)	(0.002)	(0.002)
β_5	$\ln g$	0.381	0.383	0.383
		(0.024)	(0.025)	(0.025)
α_0	*constant*	−0.006	−0.010	−0.004
		(0.012)	(0.012)	(0.012)
α_1	t	−0.018	−0.014	−0.018
		(0.002)	(0.003)	(0.002)
α_2	t^2	1.156e-4	4.02e-4	0.74e-4
		(1.05e-4)	(2.37e-4)	(1.01e-4)
α_3	$\ln q$	0.640	0.594	0.646
		(0.092)	(0.103)	(0.092)

Overall Change in Menu of Models Offered

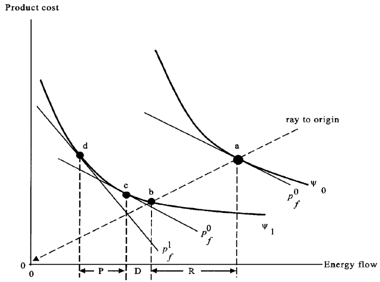
- Room air conditioners at five-year intervals



- Heavy dot: mean characteristics
- Moved to origin (overall innovation)+ flatter (directional inn)
- Recall that movements along the curve is model substitution

Decomposition of Characteristics Innovation

- Assume a optimal at t_0& ψ_0
- Line p_f^0 represents relative "price" of energy relevant for choice of optimal energy efficiency
- Technical improvement: ψ_0 to ψ_1
- Energy price now as p_f^1
- $\Rightarrow$ Optimal energy flow point d



Decomposition of Characteristics Innovation

- Improvement b/w a & d into distances R, D, P
- R: improvement in up-front product costs and energy operating costs: overall technological change
- R: rate of decrease in total cost of good to its user (product plus energy cost)
- Point c: same tangency as old price line
- D: effect on energy use between time t_0 and t_1
- D: "directional technological change"
- P: "model substitution": from change in prices from p_0^f to p_1^f

$$\frac{\dot{f}^*}{f^*} = \underbrace{\frac{1}{1-\beta_1}(\dot{\alpha} + \dot{\beta}_1 ln(f^*) + \dot{\beta}_2 ln(c^*))}_{R} + \underbrace{\frac{1}{1-\beta_1}\frac{\dot{\beta}_1}{\beta_1}}_{D:slop} - \underbrace{\frac{1}{1-\beta_1}\frac{\dot{p_f}}{p_f}}_{P:price}$$

Decomposition of Annual Changes in Energy Efficiency

- Calculate R, D, P, for each time
- For each product estimate:

$$\Delta ln(\bar{e}_t) = \sigma + \mu R_t + \zeta D_t + l_{0t} \sum_{j=0}^{\hat{J}} \tau_{0j} \frac{1}{1-\beta_{1t}} \Delta ln(p_{t-j}) + l_{1t} \sum_{j=0}^{\hat{J}} \tau_{1j} \frac{1}{1-\beta_{1t}} \Delta ln(p_t$$

- LHS: rate of change in mean energy-efficiency
- p: price of electricity or natural gas to prod. inputs
- l_0 dummy energy-efficiency labeling was not yet in effect
- l_1 dummy variable indicating that labeling was in effect
- Δs dummy energy-efficiency standards had been legislated but not yet achieved (s equals 1 for $1987 \leq t \leq 1990$)
- $j = \hat{J}$ most distant price lag
- H_0: mean model is optimal : $\sigma = 0$, $\mu = 1, \zeta = 1, \sum \tau_1 = 1$

Factors Affecting Changes in Energy Efficiency

Parameter	Explanatory variable	Description	Room air conditioners	Central air conditioners	Gas water heaters
η_0	$\frac{1}{1-\beta_1} l_0 \Delta \ln p$	prelabeling price effect	0.001 (0.630)	1.394 (0.423)	0.326 (0.529)
η_1	$\frac{1}{1-\beta_1} l_1 \Delta \ln p$	postlabeling price effect	1.175 (0.391)	—	0.577 (0.277)
θ	Δs	standards	0.024 (0.025)	—	0.017 (0.007)
μ	R_t	rate of innovation	0.055 (0.417)	0.844 (0.882)	−2.045 (2.872)
ξ	D_t	direction of innovation	−0.053 (0.145)	0.047 (0.059)	0.479 (0.761)
σ	*constant*		0.007 (0.007)	0.001 (0.026)	0.007 (0.009)
		# observations	35	21	31
	$1-U$	goodness of fit	0.67	0.66	0.61

Historical Effects of Price & Standards on Efficiency

- Historical simulations of cumulative percent changes in energy efficiency using previous estimates

	Room air conditioners		Central air conditioners		Water heaters	
	Relative to 1973	Share of total change	Relative to 1973	Share of total change	Relative to 1973	Share of total change
Total change (%) (baseline)	29.7	—	58.9	—	11.2	—
	(4.5)		(3.5)		(2.4)	
Price-induced portion (%)	8.2	28	16.1	27	5.1	46
	(5.0)		(5.0)		(2.4)	
Standards-induced portion (%)	7.1	24	—	—	7.6	68
	(3.1)				(1.8)	
Autonomous portion (%)	12.7	43	36.8	62	−1.1	−10
	(2.7)		(3.7)		(1.9)	

- Substantial positive relationship price of energy & rate of energy-efficiency improvements
- Standard labeling: significant
- Energy price 1973 if kept, 25%-50% of efficiency not happen
- Energy standard (direct energy-efficiency) modest positive
- Autonomous drivers of energy efficiency explain up to 62% of total change in energy efficiency

Introduction

- Popp, D. (2002). "Induced innovation and energy prices". American Economic Review 92 (1), 160-180.
- Policy environmental concern: induced technological change or autonomous?
- U.S. patent data from 1970-1994 for effect of energy prices on energy-efficient innovations
- Need to endogenize stock of knowledge to evaluate inducement

Modeling and Data

- Patents granted a classification number
- 300 main classification groups, 50,000 subclassifications
- From Department of Energy identify energy field
- Then sorted to 11 distinct technology groups: 6 energy supply (solar energy), 5 groups energy demand (methods of reusing industrial waste heat)

Summary Patent Data

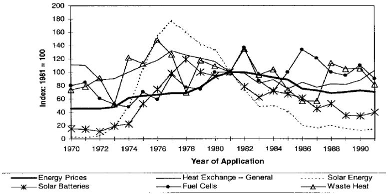
- Annual count of successful patent applications

Privately Held U.S. Patents (Sorted by Year of Application) Technology Group	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Supply Technologies											
Coal liquefaction: producing liquid fuels	42	37	27	28	51	45	107	88	114	77	97
Coal gasification: producing gaseous fuels	14	24	16	20	38	31	42	45	53	32	38
Solar energy	6	5	10	36	104	218	321	367	333	295	278
Batteries for storing solar energy	18	17	13	23	27	63	89	117	142	119	112
Fuel cells	43	46	33	28	26	38	32	52	42	40	54
Using waste as fuel	63	53	52	52	49	29	32	34	41	40	50
Demand Technologies											
Recovery of waste heat for energy	17	18	21	12	28	26	34	29	16	27	25
Heat exchange: general	425	423	340	346	382	418	450	505	479	462	443
Heat pumps	0	2	8	4	7	8	20	17	32	24	21
Stirling engines	13	13	12	9	17	11	17	11	12	11	18
Continuous casting processing of metal	84	115	67	63	48	46	43	37	40	45	44

Technology Group	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Supply Technologies													
Coal liquefaction: producing liquid fuels	100	82	74	70	34	20	12	14	22	16	10	12	8
Coal gasification: producing gaseous fuels	27	25	22	15	18	10	16	10	14	9	4	5	2
Solar energy	208	151	102	104	85	42	35	44	33	26	32	27	23
Batteries for storing solar energy	119	93	74	86	80	73	54	63	42	41	48	53	20
Fuel cells	54	74	47	39	54	72	65	54	51	60	49	61	58
Using waste as fuel	44	58	50	44	46	61	83	69	84	102	98	93	60
Demand Technologies													
Recovery of waste heat for energy	23	31	22	24	17	13	13	26	24	24	19	25	22
Heat exchange: general	382	377	317	338	286	323	297	315	311	337	391	428	350
Heat pumps	30	18	11	8	14	15	11	5	14	18	22	14	17
Stirling engines	21	30	21	19	13	13	19	10	12	18	11	12	5
Continuous casting processing of metal	43	49	61	62	46	80	39	58	38	33	38	33	31

Summary Patent Data

- Energy prices



- High correlation b/w energy price and patent

Technology Group	Correlation with: Current Prices	Prices Lagged 1 Year	Prices Lagged 2 Years
Coal liquefaction	0.424	0.251	0.034
Coal gasification	0.059	−0.179	−0.299
Solar energy	0.325	0.100	−0.148
Solar batteries	0.675	0.548	0.331
Fuel cells	0.517	0.611	0.645
Waste as fuel	−0.073	0.028	0.162
Waste heat	0.283	0.055	−0.151
Heat exchange: general	−0.175	−0.297	−0.413
Heat pumps	0.544	0.373	0.120
Stirling engine	0.662	0.597	0.463

Modeling

- $EPAT_{i,t}$ number of successful patent, energy tech i
- $TOTPAT_t$ number of successful patents
- $P^*_{E,t}$ price of energy
- $K_{i,t-1}$ stock of knowledge accumulated

$$log(\frac{EPAT_{it}}{TOTPAT_t}) = \phi_i + \gamma(1-\lambda)log(P^*_{E,t}) + \theta log(K_{i,t-1}) + \eta(1-\lambda)log(Z^*_{it}) + \lambda^t \mu^0 +$$

- $i = 1, \cdots, 11; t = 1, \cdots, 20$
- Adaptive expectations for prices

$$P^*_{E,t} = P_{E,t} + \lambda P_{E,t-1} + \lambda^2 P_{E,t-1} + \cdots + \lambda^{t-1} P_{E,1}$$

- $\gamma(1-\lambda)$ short-run price elasticity of energy innovation
- γ long run elasticity

$$Z^*_{i,t} = Z_{i,t} + \lambda Z_{i,t-1} + \lambda^2 Z_{i,t-2} + \cdots + \lambda^{t-1} Z_{i,1}$$

Patent Citations and the Existing Stock of Knowledge

- Patent citation: usefulness of patents
- Cited patents good indicator of knowledge utilized by inventor
- $n_{i,CTD}$: number of potentially cited patents applied for in year CTD
- $n_{i,CTG}$: number of potentially citing patents granted in year CTG
- Citations in each group: $n_{i,CTD,CTG}$
- Probability of citation for patents within each group:

$$p_{i,CTD,CTG} = \frac{c_{i,CTD,CTG}}{(n_{i,CTD})(n_{i,CTG})}$$

Patent Citations and the Existing Stock of Knowledge

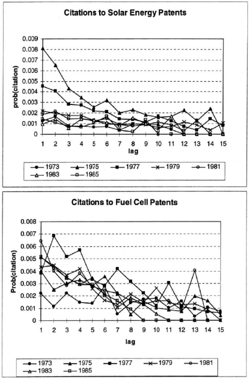
- Estimate probability that a patent would be cited

$$p(i, CTG, CTD) = \alpha(i, CTG, CTD)e^{-\beta_1(CTG-CTD)} \times \Big[1 - e^{\beta_2(CTG-CTD}$$

- β_1: rate of decay of knowledge as it becomes obsolete
- β_2: rate at which newly produced knowledge diffuses through society
- $\alpha(i, CTG, CTD)$ include:
    - Productivity param: usefulness of knowledge represented in patent (of year CTD) being cited $(\alpha_{i,CTD})$
    - frequency with which patents applied for in citing year cite earlier patents α_{CTG}
    - frequency of citations within each technology group α_i

Probability of Citations

- Granted years

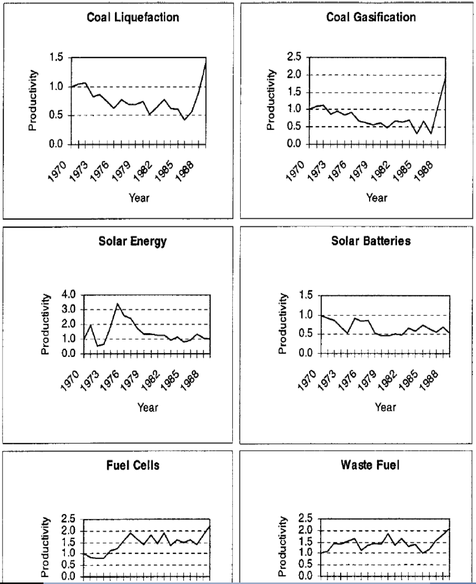


- Estimate values of productivity parameter:

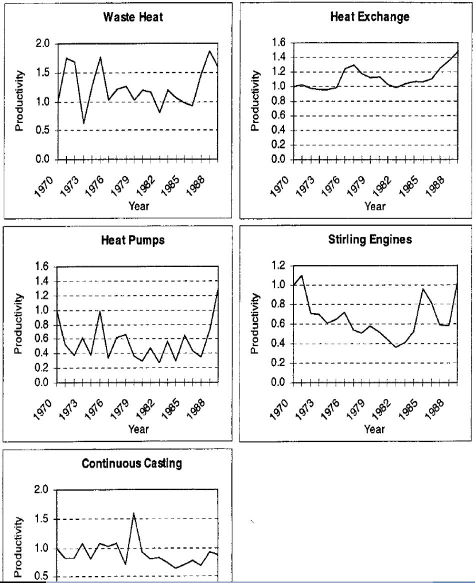
$$p_{i,CTD,CTG} = \alpha_i \alpha_{i,CTD} \alpha_{CTG} e^{-\beta_1 (CTG-CTD)} \times \left[1 - e^{-\beta_2 (CTG-CTD)}\right] + \varepsilon$$

- α_{1970} is normalized to 1 for cited years
- $\alpha_{1974-1975}$ is normalized to 1 for citing years
- α_i is normalized to 1 for continuous casting patents.

Productivity Estimates



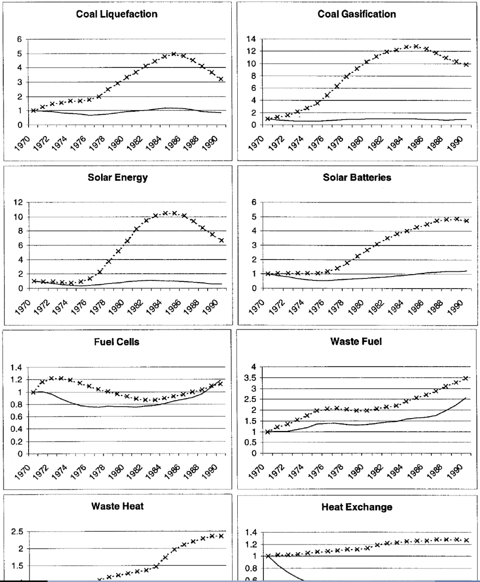
Productivity Estimates



Constructing the Knowledge Stocks

- Stock of knowledge for each technology group two cases
  1. $K_{it} = \sum_{s=0}^{t} PAT_{i,s} e^{-\beta_1(t-s)} \times \left[1 - e^{-\beta_2(t-s)}\right]$
  2. $K_{it} = \sum_{s=0}^{t} \alpha_{i,s} PAT_{i,s} e^{-\beta_1(t-s)} \times \left[1 - e^{-\beta_2(t-s)}\right]$
- Stock 1 has no control for quality of patents.

Stock of Knowledge



Results

- Estimate induced innovation

$$log\left(\frac{EPAT_{i,t}}{TOTPAT_t}\right) = \phi_i + \gamma(1-\lambda)log(P^*_{E,t}) + \theta log(K_{i,t-1}) + \eta(1-\lambda)log(Z^*_{i,t}) + \lambda^t \mu$$

- Knowledge stocks: control for supply-side factors
- Stock correlated with lagged energy prices ⇒ lagged values as IV
- Unweighted knowledge stock ⇒ just half of the effect of the 1973 oil price shock on innovation would have passed by 1987!
- Weighted stock ⇒ short-run price elasticity is double
- Reaction to higher energy prices is fairly quick, patienter rush to apply

Induced Innovation Regression Results

- Dependent variable: percentage of total domestic patent applications in each technology group

Independent Variables	Unweighted Stock of Patents	Weighted Stock of Patents
Constant	−9.015	−7.311
	(−12.362)	(−46.625)
Energy prices	0.028	0.060
	(2.146)	(2.852)
Lagged knowledge stock	0.719	0.838
	(25.612)	(72.323)
Government R&D	0.006	−0.009
	(0.968)	(−1.741)
Truncation error	1.924	−1.203
	(2.445)	(−5.054)
λ	0.933	0.829
	(18.905)	(13.662)
Long-run energy elasticity	0.421	0.354
Long-run government R&D		

The Returns to R&D

- Price and quality of stock are important
- Omitting stocks lead to lower estimates of effect of prices on patenting activity. (price, higher patent, higher stock, higher follow up patents)
- Regressions without stock of knowledge

Independent Variables	No Control for Productivity	Time Trend
Constant	76.961	−101.147
	(0.646)	(−1.901)
Energy prices	−0.116	−0.241
	(−0.708)	(−3.211)
Time trend		23.477
		(2.005)
Government R&D	−0.001	−0.014
	(−0.554)	(−1.977)
Truncation error	−85.033	−7.394
	(−0.714)	(−1.936)