Optimal Carbon Taxation and Energy Substitution

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Background

- CO2 emissions released in the air as a byproduct of production contributes to a climate externality:
  - Problem because it deteriorates the earth's ecosystem but damages are not tied to the source of pollution.
- Standard pigouvian theory suggests to put a price on pollution (a carbon tax) equal to marginal externality damages:
  - Not feasible because it would require putting monitoring devices on every polluting capital (too costly).
- **In practice**, a tax is levied on polluting inputs, specifically fossil fuels like coal, natural gas and oil:
  - Coal releases more emissions in the air than natural gas and oil for a given equivalent energy unit.
  - Carbon tax reflects these differences in emission intensity.

fuel emission

Overview of Contribution

1. I Provide novel empirical evidence on plant's usage of fossil fuels that isn't captured by standard models of production:
   - How plants mix between different fuels at any given time.
   - How plants switch between different fuels across time.
2. I develop a stylized model that captures the main novelties of the data and solve an optimal taxation problem to show that an externality tax on fossil fuels should reflect these peculiarities and departs from a pigouvian "carbon" tax.

Specific claims - Empirical

Empirical evidence:

1. 70 % of plants use a single fuel in a given year.
2. 50% of plants switch between fuels at least once.
   - Switching between fuels is positively correlated with productivity.

Reminiscent of a world with no complementarity and perfect substitutability but costly switching at the plant level.

- Story not about technological complementarity but about prices and access $\rightarrow$ important policy implications.

Specific claims - Optimal tax

1. Imagine a world with two fuels (dirty and clean) that are perfect substitutes but where plants need to pay a fix cost to switch between fuels.

$$ghg = \gamma_d e_d + \gamma_c e_c$$
$$\gamma_d > \gamma_c$$

2. **No switching:** Optimal tax is a pigouvian carbon tax.

$$\underbrace{\frac{\tau_d^*}{\tau_c^*}}_{\text{Optimal Tax}} = \frac{\gamma_d}{\gamma_c} = \underbrace{\frac{\tau_d^{pigou}}{\tau_c^{pigou}}}_{\text{Carbon Tax}}$$

Specific claims - Optimal tax

1. Imagine a world with two fuels (dirty and clean) that are perfect substitutes but where plants need to pay a fix cost to switch between fuels.

$$ghg = \gamma_d e_d + \gamma_c e_c$$
$$\gamma_d > \gamma_c$$

2. **switching:** Optimal tax puts a higher relative tax rate on dirty fuel than a pigouvian carbon tax.

$$\underbrace{\frac{\tau_d^*}{\tau_c^*}}_{\text{Optimal Tax}} > \frac{\gamma_d}{\gamma_c} = \underbrace{\frac{\tau_d^{pigou}}{\tau_c^{pigou}}}_{\text{Carbon Tax}}$$

- Presence of costly switching without technological complementarity implies a larger marginal gain to increase τ_d/τ_c relative to a world with no switching.

My findings are at odds with recent results

Literature claims carbon tax is optimal solution to climate externality:

1. Dynamic feedback between the carbon cycle, climate and aggregate output (Nordhaus 2007).
2. Other distortionary taxes (Barrage 2020).
3. Presence of multiple fossil fuels with interfuel substitution (Golosov et al. 2014, 2020).

Literature makes strong assumptions

All have in common strong assumptions on aggregate production function (i.e. nested CES) which features polluting inputs such as fossil fuels.

- Restricted plant-level substitution behaviors required for aggregation.

I show that in my model of heterogeneous firms, the equilibrium is proportionally equivalent to a model with an aggregate CES production function in both fuels only if **switching is not possible** (similar to Houthaker 1955).

Dataset used

- Indian survey of industries (ASI):
  - All manufacturing plants with at least 100 workers and a sample of plants with less than 100 workers.
  - Repeated cross-section: 2009-2018
    - Following Orr 2020, create panel identifiers by matching plants across years based on closing and opening values of observables.
- Four specific industries:
  1. Steel and Iron
  2. Cement
  3. Aluminium
  4. Pulp & Paper

Why these industries?

- Very energy-intensive manufacturing industries (Aldy and Pizer 2015, IPCC 2018)
- Fairly homogeneous output: easier to compare plants within industries.
- Use fossil fuels in specific ways:
  - To generate heat required to transform crude resources into refined products.
  - Can use different fuels in that heating process.

Usage examples

Why India?

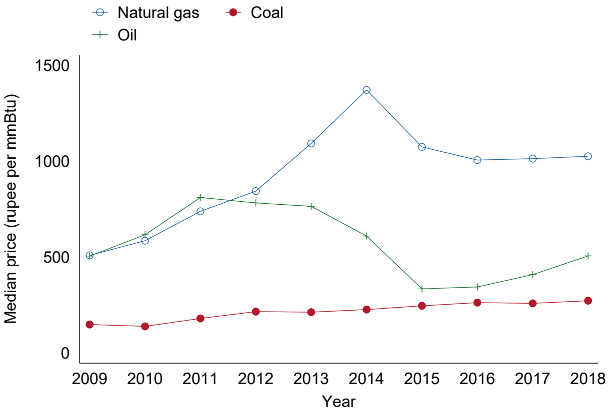
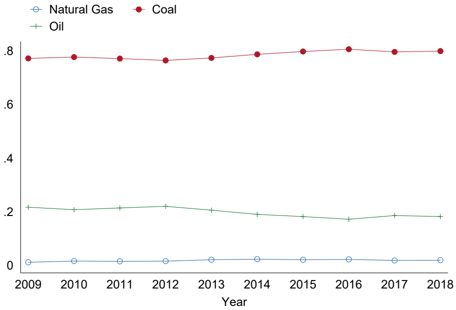
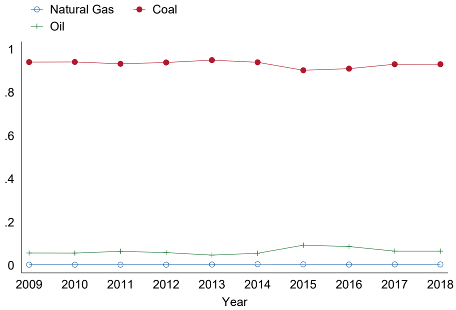


Figure: Coal is much cheaper than Natural Gas

Why India?



(a) Spending Shares



(b) Quantity Shares

Figure: Indian plants heavily use coal relative to other fuels

Canadian plants pollute much less for one mmBtu of energy

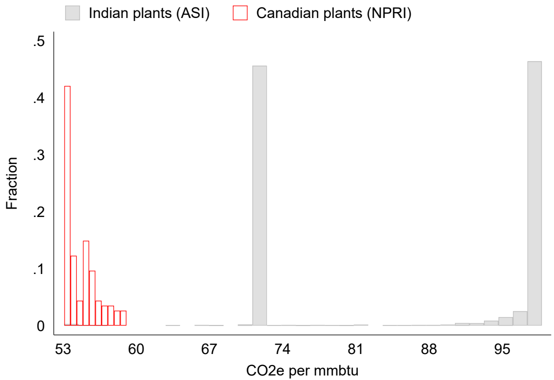
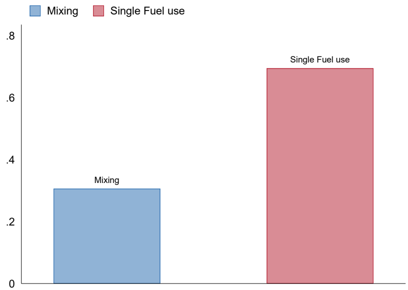


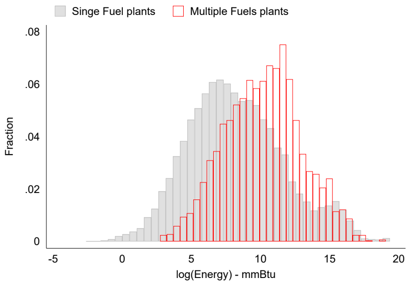
Figure: Cement manufacturing

All industries
Spatial Distribution of Natural Gas

1. 70% of plants don't mix between fuels at any given time and those that do are typically larger



(a) Proportion of single fuel usage vs. mixing



(b) Distribution of energy usage (single vs mixing plants)

Switching Definition

I define fuel switching as follows between two periods:

1. Single to Single (new fuel)
2. Single to mixing
3. Mixing to single
4. Mixing to Mixing (new mix)

2. Half of the plants switch between fuels at least once in their lifetime

	Never Switch	Switch	Total
Number	526	643	1,169
Fraction	0.45	0.55	1

Table: Proportion of unique plants who switch at least once

Single to Mix \ Mix to Single	No	Yes	Total
No	576	113	689
Yes	114	366	480
Total	690	479	1169

Table: Mixing as transition phase?

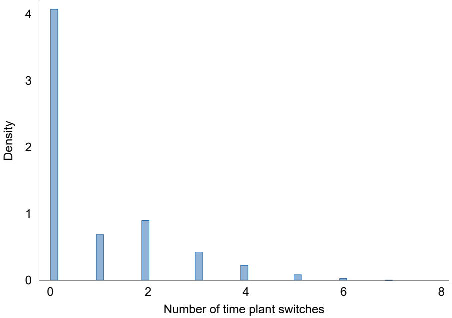


Figure: Distribution of switching freqhency

Extra Evidence

2.1 Switching matters to explain variation in carbon content of energy

1. Normalize energy to 2009 energy levels for each plants. Then for a given plant, GHG emmissions (G) are

$$G_{it} = \sum_{s}^{n} \gamma_s E_{ist}$$

$$\Delta G_{it}(\bar{E}_{i,2009}) = \sum_{s}^{n} \gamma_s (E_{ist} - E_{ist-1})$$

2.

$$\begin{aligned}\Delta G_{it}(\bar{E}_{i,2009}) &= \Delta G_{it}(\bar{E}_{i,2009})\mathbb{I}(\text{Switch}) + \Delta G_{it}(\bar{E}_{i,2009})\mathbb{I}(\text{Does not switch}) \\ &= \Delta G_{ist}(\bar{E}_{i,2009}) + \Delta G_{inst}(\bar{E}_{i,2009})\end{aligned}$$

2.1 Switching matters to explain variation in carbon content of energy (graphs)

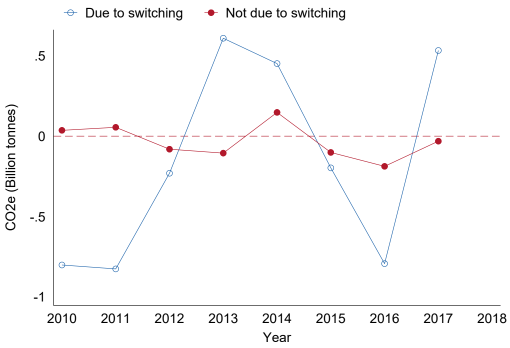


Figure: Decomposition of change in GHG emissions

2.1 Switching matters to explain variation in carbon content of energy (graphs)

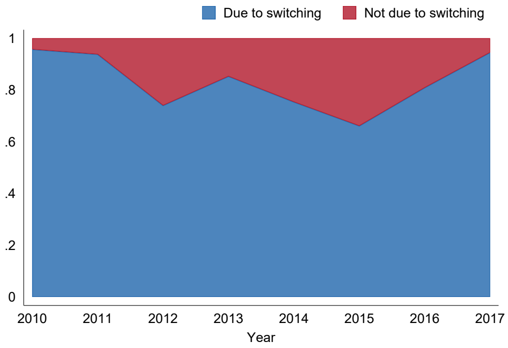


Figure: Proportion of change in GHG emissions due to Switching and not Switching

2.3 Fuel switching is positively correlated with productivity (Table)

Estimate revenue production function using ACF (2015) while treating energy as fixed within periods.

$$logY_{it} = \alpha_l logL_{it} + \alpha_k logK_{it} + \alpha_m logM_{it} + \alpha_e logE_{it} + \lambda_j + \omega_{it} + \epsilon_{it}$$

Table: T-test for Difference in mean productivity (non-switchers minus switchers)

	(1) Any period	(2) Year of switching	(3) Year before switching
Difference in mean productivity	0.0827***	0.0473*	0.0690***
	(5.09)	(2.35)	(3.38)
Observations	6810	6810	5688

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robustness

2.3 Switching behavior is positively correlated with productivity (Graphs)

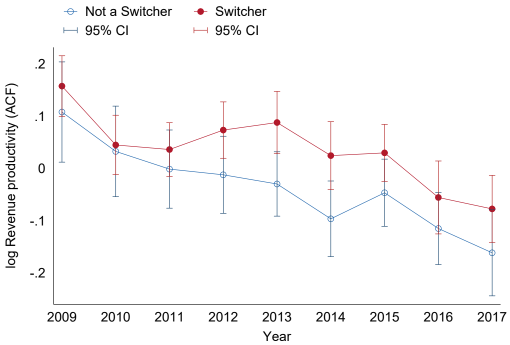


Figure: Any period

Extra Evidence

Stylized Model Overview

- Heterogeneous firms only use one of two fossil fuels to produce output.
- Switching between fuels possible by paying a fixed cost.
- Fuel switching rule based on productivity-efficiency argument.
- Externality with Partial Equilibrium in fuel prices (Diamond and Mirrlees 1971).

Assumptions

- There are two fuels: dirty (d) and clean (c)
- Continuum of firms indexed by productivity φ that produce output using fossil fuels only.
  - $N_d \in (0,1)$ are initially using the dirty fuel: φe_d
  - $N_c \in (0,1)$ are initially using the clean fuel: φe_c
- Firms engage in monopolistic competition and maximize profits, taking fuel prices as given:

$$\max\left\{\max_{e_d}\left\{p(\varphi)\varphi e_d - p_d e_d\right\}, \max_{e_c}\left\{p(\varphi)\varphi e_c - p_c e_c - \kappa\right\}\right\}$$
$$\equiv \max_{e_d, e_c}\left\{p(\varphi)\varphi(e_d + e_c) - \tilde{p}_d e_d - \tilde{p}_c e_c - 1(e_c > 0)\kappa\right\}$$

Preferences and Externality

- Representative consumer with CES preferences over varieties:

$$\tilde{Y} = \big(1 - D(ghg)\big)Y$$
$$Y = \Big(\int_{\Phi_s} y_d(\varphi)^{\frac{\rho-1}{\rho}} dF(\varphi) + \int_{\Phi_c} y_c(\varphi)^{\frac{\rho-1}{\rho}} dF(\varphi)\Big)^{\frac{\rho}{\rho-1}}$$

Where $D(ghg) \in (0,1)$ maps aggregate emissions to damages in units of the final good (Nordhaus 2007, Golosov et al. 2014) and where aggregate emissions are defined as follow:

$$ghg = \gamma_d E_d + \gamma_c E_c$$
$$E_s = \int_{\Phi_s} e_s(\varphi) dF(\varphi)$$
$$s \in \{d, c\}$$

Aggregation

- Rep. worker has exogenous income normalized to 1 and takes aggregate GHG emissions as given:

$$PY = 1$$
$$Y = 1/P$$

Where P is the CES price index.

$$P = \left(\int_{\Phi_d} p_d(\varphi)^{1-\rho} dF(\varphi) + \int_{\Phi_c} p_c(\varphi)^{1-\rho} dF(\varphi) \right)^{\frac{1}{1-\rho}}$$

Fuel switching rule

1. Firms will only switch if the dollar price of the new fuel is cheaper than the current fuel.
2. Conditional on 1), there is an endogenous productivity threshold Ω for firms to switch:
   - More productive firms benefit more from reduction in variable costs.

Example: if $p_d > p_c$

$$E_d = \underbrace{N_d \int_0^{\Omega} \varphi^{\rho-1} dF(\varphi)}_{\tilde{\varphi}_d^{\rho-1}} \left(\frac{\rho-1}{\rho}\frac{P}{\tilde{p}_d}\right)^{\rho} Y$$

$$E_c = \underbrace{\left[N_d \int_{\Omega}^{\infty} \varphi^{\rho-1} dF(\varphi) + N_c \int_0^{\infty} \varphi^{\rho-1} dF(\varphi)\right]}_{\tilde{\varphi}_c^{\rho-1}} \left(\frac{\rho-1}{\rho}\frac{P}{\tilde{p}_c}\right)^{\rho} Y$$

More details

Government's optimal tax problem:

Since the model features partial equilibrium in fuel prices, the government effectively chooses fuel prices (Diamond and Mirless, 1971). Morevover, since the government only price the externality, fuel prices and taxes can be used interchangeably:

$$\max_{p_d, p_c} \tilde{Y}$$

$$s.t. \tilde{Y} = \big(1 - D(ghg)\big)Y$$

$$Y = \frac{1}{P}$$

Key equilibrium condition:

$$\underbrace{\frac{\partial ghg/\partial p_d}{\partial ghg/\partial p_c}}_{\text{Marginal relative gains: } MRG} = \underbrace{\frac{\partial P/\partial p_d}{\partial P/\partial p_c}}_{\text{Marginal relative losses: } MRL}$$

A useful benchmark

The model where there is no switching ($\kappa \to \infty$) is proportionally equivalent to a model with an aggregate production function that takes aggregate fuel quantities as inputs which is reminiscent of most optimal carbon taxation papers in the literature:

$$Y = \tilde{\varphi}\Big(N_d^{\frac{1}{\rho}} E_d^{\frac{\rho-1}{\rho}} + N_c^{\frac{1}{\rho}} E_c^{\frac{\rho-1}{\rho}}\Big)^{\frac{\rho}{\rho-1}}$$

$$N_d + N_c = 1$$

Where

$$\tilde{\varphi} = \Big(\int_0^\infty \varphi^{\rho-1} dF(\varphi)\Big)^{\frac{1}{\rho-1}}$$

Optimal Taxation - Benchmark

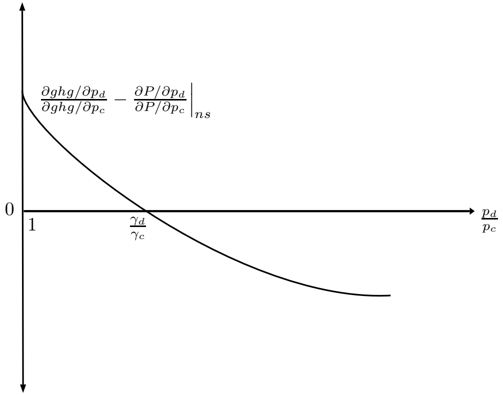


Figure: Optimal ratio of fuel prices

$$\frac{\partial ghg}{\partial p_d}$$

Direct effect:

$-\gamma_d f(p_d)$

$f'(p_d) < 0$

Effect through price index:

$$\frac{\partial P}{\partial p_d}$$

Optimal Taxation - Switching

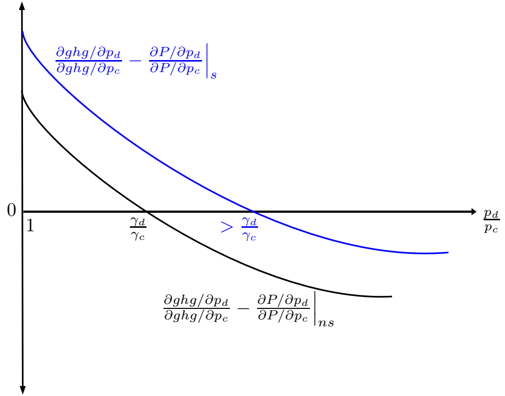
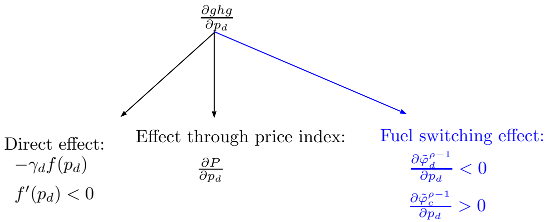


Figure: Optimal ratio of fuel prices



Going forward

Develop a quantitative model that maps to the data, where aggregation is similar to stylized model but where fuel switching is analogous to a discrete technological change (ex: Midrigan and Xu 2014):

$$V(x_t, k_t, f_t) = \max_{l_t, l_t, e_t, k_{t+1}, f_{t+1}} \{\pi_t(l_t, m_t, k_t, e_t(f_t), x_t) + \mathbb{E}V(x_{t+1}, k_{t+1}, f_{t+1})\}$$

- supply of fossil fuels: spatial distribution of fixed costs based on existing distribution networks.
- General equilibrium fuel prices.
- Endogenous distribution of N_d and N_c (see next slide).

Why do plants use natural gas?

Some plants decide to use natural gas despite it's high price relative to Coal.

1. Capital required to use coal (kiln, furnaces) depreciates faster that capital required to use natural gas.
2. Plants take expectation over future regulation and expect the price of coal to increase relative to natural gas
3. Some plants are inherently better at using natural gas (fuel-specific productivity).

Conclusion

1. I Highlight some novel empirical evidence on plants' use of fossil fuel and how it evolves over time.
   - Low complementarity due to many single fuel plants
   - High substitutability due to switching across fuels over time
2. I Show that taking into account these facts has non-trivial impact on optimal environmental taxation
   - Particularly that low complementarity/high substitutability between fuels implies that incentivizing firms to switch across fuels is an important component of the gains from environmental taxation, and that a carbon tax does not lead to the optimal incentive level.

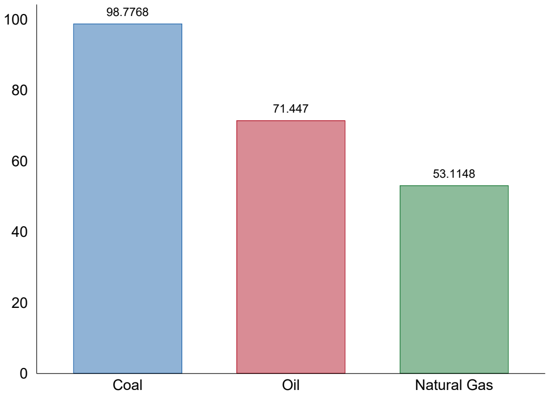
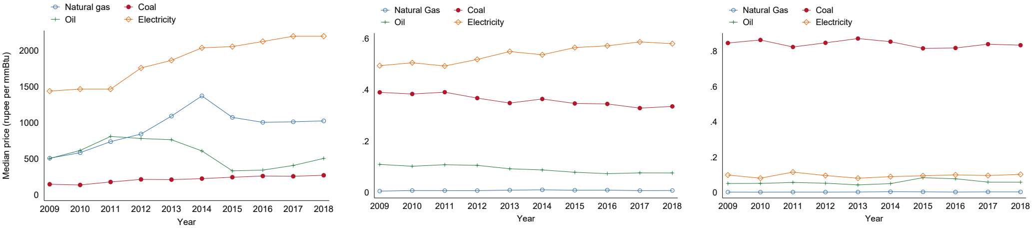


Figure: kg of CO2e per mmBtu of each fuel (EPA 2018)

back to main

Why India?



(a) Eenergy prices: Indian rupees per mmBtu

(b) Aggregate energy spending shares

(c) Aggregate energy quantity (mmBtu) shares

Figure: Electricity provides different form of energy

back to main

Marginal effects, probability of switching (current period)

Table: Marginal effects, probability of switching (current period)

	(1) Same period	(2) Same period	(3) Same period
Collateral requirement for a loan (percentage of loan amount)	-0.000206***	-0.000195**	-0.000170**
	(-3.33)	(-3.14)	(-2.74)
Cash	0.00264	0.00251	0.000100
	(1.03)	(0.98)	(0.04)
Electricity	0.0225***	0.0221***	0.0135***
	(6.69)	(6.56)	(3.77)
Fuels	0.0116***	0.0120***	0.0113***
	(5.19)	(5.29)	(4.65)
Number of workers	-0.0295***	-0.0306***	-0.0160**
	(-5.02)	(-5.15)	(-2.59)
Age	0.00469	0.00483	0.00797
	(0.75)	(0.78)	(1.28)
Price of Oil		0.00996	0.00860
		(0.62)	(0.54)
Price of Natural Gas		-0.0376***	-0.0272**
		(-3.64)	(-2.65)
Price of Coal		0.0229	0.0164
		(1.51)	(1.10)
industry dummies	No	No	Yes
Observations	5252	5252	5252

t statistics in parentheses

All independent variables are in logs

$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

back to main | switching next period

Marginal effects, probability of switching (Next period)

Table: Marginal effects, probability of switching (next period)

	(1) Next period	(2) Next period	(3) Next period
Collateral requirement for a loan (percentage of loan amount)	-0.000191**	-0.000162*	-0.000139^{+}
	(-2.67)	(-2.25)	(-1.94)
Cash	-0.00105	-0.000312	-0.00318
	(-0.36)	(-0.11)	(-1.05)
Electricity	0.0200***	0.0200***	0.0112**
	(5.25)	(5.23)	(2.75)
Fuels	0.0158***	0.0162***	0.0153***
	(6.19)	(6.23)	(5.47)
Number of workers	-0.0305***	-0.0357***	-0.0189**
	(-4.47)	(-5.18)	(-2.65)
Age	-0.00609	-0.00384	-0.00123
	(-0.90)	(-0.57)	(-0.18)
Price of Oil		0.0638***	0.0630***
		(3.41)	(3.40)
Price of Natural Gas		-0.0348**	-0.0240*
		(-3.02)	(-2.10)
Price of Coal		-0.0156	-0.0230
		(-0.93)	(-1.39)
industry dummies	No	No	Yes
Observations	4315	4315	4315

t statistics in parentheses

All independent variables are in logs

$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

back to main | switching any period

Marginal effects, probability of switching (Any period)

Table: Marginal effects, probability of switching (any period)

	(1) any period	(2) any period	(3) any period
Collateral requirement for a loan (percentage of loan amount)	-0.000430***	-0.000385***	-0.000322***
	(-5.65)	(-5.04)	(-4.27)
Cash	0.00488	0.00572+	0.000189
	(1.54)	(1.82)	(0.06)
Electricity	0.0559***	0.0549***	0.0381***
	(14.79)	(14.57)	(9.36)
Fuels	0.0317***	0.0316***	0.0311***
	(12.12)	(11.97)	(11.05)
Number of workers	-0.0670***	-0.0713***	-0.0397***
	(-9.57)	(-10.13)	(-5.43)
Age	-0.0000978	0.00173	0.00731
	(-0.01)	(0.23)	(0.99)
Price of Oil		0.0367+	0.0350+
		(1.87)	(1.83)
Price of Natural Gas		-0.113***	-0.0906***
		(-7.59)	(-6.20)
Price of Coal		0.00550	-0.00775
		(0.28)	(-0.40)
industry dummies	No	No	Yes
Observations	5252	5252	5252

t statistics in parentheses

All independent variables are in logs

$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

back to main

Productivity threshold

$$\Omega = \left[\frac{\kappa}{P^{\rho} Y \Gamma(\rho)} \frac{1}{p_c^{1-\rho} - p_d^{1-\rho}}\right]^{\frac{1}{\rho-1}}$$

1. If $p_d > p_c$, $\Omega > 0$
2. If $p_d < p_c$, $\Omega < 0$

back to main case where $p_d > p_c$

Formal switching rules: $p_d > p_c$

New fuel			
Original fuel		d	c
	d	$\varphi < \Omega$	$\varphi > \Omega$
	c	$\varphi < -\Omega$	$\varphi > -\Omega$

$$E_d = \underbrace{\left[N_d^* \int_0^{\Omega} \varphi^{\rho-1} dF(\varphi) + N_c \int_0^{-\Omega} \varphi^{\rho-1} dF(\varphi)\right]}_{\tilde{\varphi}_d^{\rho-1}} \left(\frac{\rho-1}{\rho}\frac{P}{\tilde{p}_d}\right)^{\rho} Y$$

$$E_c = \underbrace{\left[N_d \int_{\Omega}^{\infty} \varphi^{\rho-1} dF(\varphi) + N_c \int_{-\Omega}^{\infty} \varphi^{\rho-1} dF(\varphi)\right]}_{\tilde{\varphi}_c^{\rho-1}} \left(\frac{\rho-1}{\rho}\frac{P}{\tilde{p}_c}\right)^{\rho} Y$$

back to main | case where $p_d < p_c$

Formal switching rules: $p_d < p_c$

	New fuel		
Original fuel		d	c
	d	$\varphi > \Omega$	$\varphi < \Omega$
	c	$\varphi > -\Omega$	$\varphi < -\Omega$

$$E_d = \underbrace{\left[N_d \int_{\Omega}^{\infty} \varphi^{\rho-1} dF(\varphi) + N_c \int_{-\Omega}^{\infty} \varphi^{\rho-1} dF(\varphi) \right]}_{\tilde{\varphi}_d^{\rho-1}} \left(\frac{\rho-1}{\rho} \frac{P}{\tilde{p}_d} \right)^{\rho} Y$$

$$E_c = \underbrace{\left[N_d \int_{0}^{\Omega} \varphi^{\rho-1} dF(\varphi) + N_c \int_{0}^{-\Omega} \varphi^{\rho-1} dF(\varphi) \right]}_{\tilde{\varphi}_c^{\rho-1}} \left(\frac{\rho-1}{\rho} \frac{P}{\tilde{p}_c} \right)^{\rho} Y$$

back to main

Examples of fossil fuel usage

1. **Cement:** Need to heat limestone, clay and sand at extremely high temperature which is done through combustion of fossil fuels in heating chambers called kiln.
2. **Steel/Aluminium:** required heat for casting metal which is done in furnaces powered by fossil fuels.
3. **Pulp & paper**: Need to generate high heat for the drying process.

back to main

Table: T-test for Difference in mean productivity (non-switchers minus switchers) - FE (Energy free)

	(1) Any period	(2) Year of switching	(3) Year before switching
Difference in mean productivity	0.150***	0.0895***	0.117***
	(8.07)	(3.87)	(5.01)
Observations	6810	6810	5688

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table: T-test for Difference in mean productivity (non-switchers minus switchers) - FE

	(1) Any period	(2) Year of switching	(3) Year before switching
Difference in mean productivity	0.105***	0.0530***	0.0485**
	(8.18)	(3.32)	(2.97)
Observations	6810	6810	5688

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table: T-test for Difference in mean productivity (non-switchers minus switchers) - OLS

	(1) Any period	(2) Year of switching	(3) Year before switching
Difference in mean productivity	0.00996	0.00652	0.00983
	(0.87)	(0.46)	(0.67)
Observations	6810	6810	5688

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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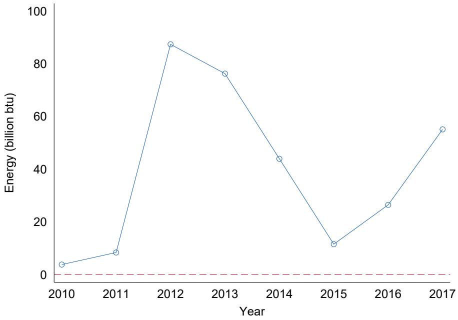
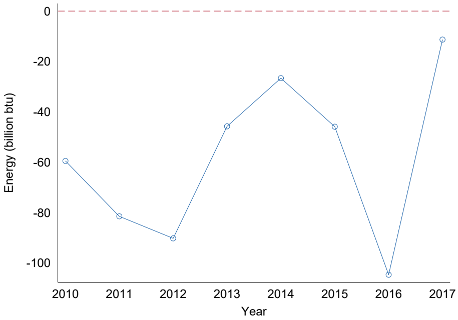
Many plants switch to Coal but also off Coal



(a) Year to Year change in mmBtu due to plants switching to Coal



(b) Year to Year change in mmBtu due to plants switching off Coal

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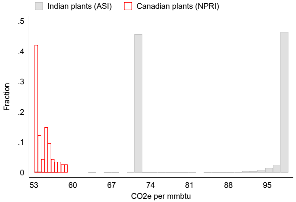
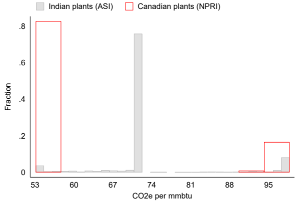
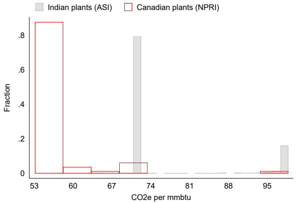


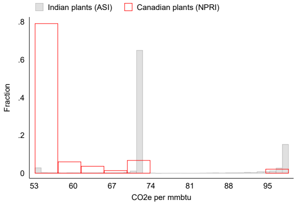
(a) Cement



(b) Aluminium



(c) Pulp & Paper



(d) Steel & Iron

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Natural Gas consumption is concentrated (ASI - Selected Industries)

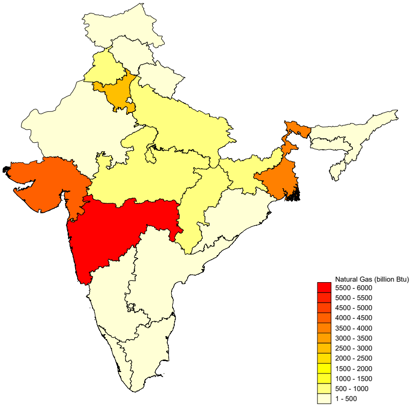

Figure: Distribution of Natural Gas consumption across states

Transportation Networks

Natural Gas transportation Networks

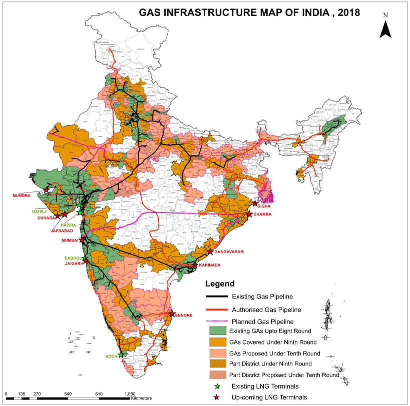

Figure: Natural Gas Transportation Network (Source: Indian Ministry of Oil and Gas)

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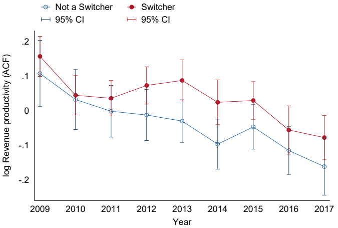
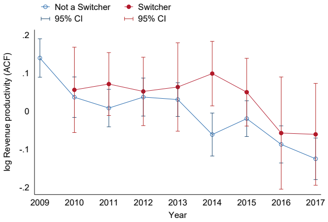
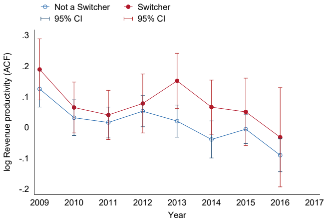
Switching and Productivity (all graphs)



(a) Any period



(b) Year of switching



(c) Year before switching

Figure: **Fuel switching is associated with higher revenue productivity**

Switching and Other vars
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