Green innovation
and the energy transition

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with D. Acemoglu, L. Barrage, D. Hemous, E. Gerschel
INTRODUCE INNOVATION IN THE CLIMATE DEBATE

• Path-Dependence in Green versus Dirty Innovation
• Government can avoid disaster by redirecting innovation towards green technologies
• Act now
• Use several instruments, not just carbon tax

  – Aghion, Dechezlepretre, Hemous, Martin, Van Reenen (2016)
  – Acemoglu, Aghion, Bursztyn, Hemous (2012)
## Path Dependence

<table>
<thead>
<tr>
<th></th>
<th>Clean</th>
<th>Dirty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Price</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ln(\text{FP})$</td>
<td>0.886**</td>
<td>-0.644***</td>
</tr>
<tr>
<td></td>
<td>(0.362)</td>
<td>(0.143)</td>
</tr>
<tr>
<td><strong>Clean Spillover</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SPILL}_C$</td>
<td>0.266***</td>
<td>-0.058</td>
</tr>
<tr>
<td></td>
<td>(0.087)</td>
<td>(0.066)</td>
</tr>
<tr>
<td><strong>Dirty Spillover</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SPILL}_D$</td>
<td>-0.160*</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td>(0.097)</td>
<td>(0.081)</td>
</tr>
<tr>
<td><strong>Own Stock Clean</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_C$</td>
<td>0.303***</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>(0.026)</td>
<td>(0.026)</td>
</tr>
<tr>
<td><strong>Own Stock Dirty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_D$</td>
<td>0.139***</td>
<td>0.542***</td>
</tr>
<tr>
<td></td>
<td>(0.017)</td>
<td>(0.020)</td>
</tr>
<tr>
<td><strong>#Observations</strong></td>
<td>68,240</td>
<td>68,240</td>
</tr>
<tr>
<td><strong>#Units (Firms and individuals)</strong></td>
<td>3,412</td>
<td>3,412</td>
</tr>
</tbody>
</table>

Notes: Estimation by Conditional fixed effects (CFX), all regressions include GDP, GDP per capita & time dummies. SEs clustered by unit.
Act now

- Without intervention, innovation is directed towards dirty inputs
- Thus the gap between clean and dirty technology widens
- Hence cost of intervention (reduced growth as long as clean technologies catch up with dirty technologies) increases
Act now: AABH 2012
Several instruments, not just carbon tax

• Two externalities:
  – Environmental externality
  – Knowledge externality (path-dependence)
• Thus need at least two instruments, not just carbon tax
ENERGY TRANSITION
with D. Acemoglu, L. Barrage, D. Hemous

• Energy transition
  – Introduce an intermediate source of energy (e.g. shale gas)
  – Should we subsidize production and research in that intermediate source?
• Analyze effects of an exogenous improvement in extraction technology for gas (shale gas boom) on aggregate pollution in short run and long run
Discrete time economy.

Final good produced according to:

\[ Y_t = e^{-\Gamma S_t} \left( (1 - \nu) Y_P^{\frac{\lambda-1}{\lambda}} + \nu \left( \tilde{A}_E E_t \right)^{\frac{\lambda-1}{\lambda}} \right)^{\frac{\lambda}{\lambda-1}}, \]

- \( Y_P \sim \) production input produced via \( Y_P = A_P L_P \)
- \( A_P, \tilde{A}_E \sim \) productivity in goods production, energy efficiency
- \( S_t \) is carbon concentration.
Golosov et al. (2014) carbon cycle:

\[ S_t = \bar{S} + \sum_{s=0}^{t+T} \left( \varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi_d)^s \right) \left( P_{t-s} + P_{t-s}^{ROW} \right), \]
Energy composite $E_t$:

$$E_t = \left( \kappa_c E_{c,t}^{\frac{\varepsilon-1}{\varepsilon}} + \kappa_s E_{s,t}^{\frac{\varepsilon-1}{\varepsilon}} + \kappa_g E_{g,t}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}.$$  

- $E_{c,t}, E_{s,t},$ and $E_{g,t}$ are coal, natural gas, and green energy, respectively.

Production of energy $i \in \{c, s, g\}$ is given by:

$$E_{i,t} = \min(Q_{i,t}, R_{i,t}).$$

- $Q_{i,t}$ is energy input (e.g., power plant); $R_{i,t}$ is resource (e.g., coal).

Resource use leads to pollution: $P_{i,t} = \xi_i R_{i,t}$ and $\xi_c > \xi_s > 0 = \xi_g$.

- Green does not pollute, and coal pollutes more than natural gas.
Energy input $i$ ("power plant") is produced according to:

$$Q_{it} = \exp \left( \int_0^1 \ln q_{ijt} \, dj \right)$$

$q_{ijt}$: Intermediate inputs (e.g., steam turbine, boiler, etc.)

- Produced by monopolist $j$ in energy sector $i$ via $q_{ijt} = A_{ijt} l^q_{ijt}$
- Monopolist’s technology $\gamma$ times more productive than fringe

Productivity in generation technologies $A_{ijt}$ endogenous

Define avg. productivity in power plant type $i$:

$$\ln A_{it} = \int_0^1 \ln A_{ijt} \, dj$$
Extraction productivity (exogenous):

- $B_{ct} \sim$ avg. productivity in coal extraction
- $B_{st} \sim$ avg. productivity in gas extraction
- Shale gas boom = exogenous increase in $B_{st}$

Denote effective productivity of energy type $i$ as:

$$C_{it} \equiv \left( A_{it}^{-1} + B_{it}^{-1} \right)^{-1}$$
Short-Run Effects

• Absent innovation (short-run), there are two opposite effects of shale gas boom:
  – Substitution effect
  – Scale effect
• Substitution effect dominates if gas sufficiently cleaner than coal
Short-Run Impact Estimates

<table>
<thead>
<tr>
<th>Total Effects of Improved Shale Extraction Technology $B_{s0}$</th>
<th>%ΔEmiss.</th>
<th>%ΔEnergy</th>
<th>%ΔCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+10% Increase in $B_{s0}$</td>
<td>-16.7%</td>
<td>+5.5%</td>
<td>-12.1%</td>
</tr>
<tr>
<td>+50% Increase in $B_{s0}$</td>
<td>-21.0%</td>
<td>+9.6%</td>
<td>-13.4%</td>
</tr>
</tbody>
</table>
Emissions and Emissions Intensity

CO2 Emissions in U.S. Electricity Generation

Year

CO2 Intensity (mt/kWh)

CO2 Emissions (mmt)

Data sources: EIA and EPA.
Long-run effects
There is a mass 1 of scientists who can decide in which sector to work

- \( S_{ft} \sim \) share working on fossil fuels generation technology
- \( S_{gt} \sim \) share working on green generation technology

Each scientist has a probability of success given by: \( \eta_i S_{it}^{\psi} \)

A successful innovator obtains a technology on energy input \( \gamma \) times more productive

- Patents last for 1 period only
- If there is no innovation, monopoly rights are allocated randomly
An innovator in the green sector obtains expected profits:

\[ \Pi_{gt} = \eta_{gt} s_{gt}^{-\psi} \left( 1 - \frac{1}{\gamma} \right) p_{gt} E_{gt} \]

An innovator in the fossil fuel sector obtains expected profits:

\[ \Pi_{ft} = \eta_{ft} s_{ft}^{-\psi} \left( 1 - \frac{1}{\gamma} \right) \left( \frac{C_{ct}}{A_{ct}} p_{ct} E_{ct} + \frac{C_{st}}{A_{st}} p_{st} E_{st} \right) \]

- Innovators in fossil technologies improve both coal and gas generation.

In equilibrium innovators must be indifferent so that:

\[ \Pi_{gt} = \Pi_{ft} \]
More advanced sector gets a larger market $\Rightarrow$ Larger profits from further innovation

- Better green technology $A_g(t-1)$ leads to more green innovation
- Better gas technology $A_s(t-1)$ leads to more fossil innovation (provided that fossil fuels are not too costly to extract relative to generation costs)

Improve in gas extraction technology $B_{st}$:
- Extraction and power plant are complements $\Rightarrow$ Higher gas extraction technology $B_{st}$ encourages innovation in gas generation $A_{st}$
Long-Run Effects

• Shale gas boom directs innovation away from both, coal and clean production technologies into gas production technologies

• In the long-run, it may move the economy from a path with declining CO2 emissions to a path with increasing CO2 emissions
Renewable and green innovation
Welfare Effect of Shale Gas Boom:
Perspective of a US social planner that takes emissions from abroad as given but internalizes foreign damages

Specify SWF as

\[ U_t = \sum_{\tau=t}^{\infty} \frac{1}{(1 + \rho_U)^{\tau-t}} \left( \frac{C_\tau^{1-\theta}}{1 - \theta} + \nu(S_t) \right) \]  

- \( s_t \) is carbon concentration. It affects consumption through damages to output
- \( \nu(S_t) \) represents welfare costs from climate damages abroad.
- Carbon cycle modeled as in GHKT.
Calibration

- We proceed in three steps:
  - We construct measures of electricity generation costs using information on electricity (only) production in the US in 2006-2010 for coal, natural gas and green sources
  - We select a number of parameters directly based on prior literature and data sources (epsilon, kappa’s)
  - We solve for the remaining parameters and initial equilibrium outcomes (initial A’s and B’s) so as to match the model with the data.

- 3 key parameters:
  - Elasticity of substitution across electricity sources $\varepsilon=1.86$ (Papageorgiou et al., 2017)
  - Decreasing return to innovation $\psi$ to match elasticity of clean to dirty innovation with respect to natural gas of 0.246
  - Discount rate $\rho$ which we take to be equal to 1.5% in most of our analysis
Effects of shale gas boom
Unmanaged boom

Panel A: Share of scientists in green

- without the boom
- with the boom

Panel B: Emissions levels, intensity, and energy (% change)

Panel C: Net output (% change)
Welfare effects

Shale boom welfare impacts in laissez-faire

400 year time horizon

Shale boom welfare impact (% cons. equiv.)

Pure rate of social time preference (%/y r)

GHKT Damages

High Damages

Shale revolution
Optimal policy: Setup

Consider a social planner who maximizes US welfare but takes emissions from ROW (and outside electricity) as given.

Two externalities $\Rightarrow$ two instruments:

- Carbon tax to correct for environmental externality
- Clean research subsidy to take into account that private value of innovation is too short-sighted
Optimal Policy: effect of the boom

Panel A: Share of scientists in green

Panel B: Optimal green research subsidy

Panel C: Optimal carbon tax
Now consider shale gas boom as given

- All simulations here take the shale gas boom as given.
- We look at effect of delaying or not the optimal policy and of using one versus two instruments
Delayed and immediate optimal policy relative to laissez-faire, high damages

Net output (% change)

-2 0 2 4 6 8 10 12

percent

2000 2020 2040 2060 2080 2100 2120 2140

Year

Laissez-faire
Immediate optimal policy
Delayed optimal policy
### Welfare compared to laissez-faire, in percentage points

<table>
<thead>
<tr>
<th></th>
<th>GKHT damages</th>
<th>High damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Policy</td>
<td>19.59</td>
<td>49.17</td>
</tr>
<tr>
<td>Delayed Policy (20 years)</td>
<td>14.85</td>
<td>34.13</td>
</tr>
</tbody>
</table>

*Note: The optimal policy increases welfare by 19.59% compared to laissez-faire, in the GHKT damages case.*

### Welfare compared to optimal policy, in percentage points

<table>
<thead>
<tr>
<th></th>
<th>GKHT damages</th>
<th>High damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Policy</td>
<td>reference</td>
<td>reference</td>
</tr>
<tr>
<td>Delayed Policy (20 years)</td>
<td>-3.65</td>
<td>-8.45</td>
</tr>
</tbody>
</table>

*Note: The delayed policy reduces welfare by 3.65% compared to the optimal policy, in the GHKT damages case.*
One versus two instruments

Constrained and optimal policy relative to laissez-faire, high damages

Panel C: Net output (% change)

- Laissez-faire
- Immediate optimal policy
- Carbon tax only
- Subsidy only
Welfare effects with 1.5% discount rate

<table>
<thead>
<tr>
<th>Welfare compared to laissez-faire, in percentage points</th>
<th>GKHT damages</th>
<th>High damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Policy</td>
<td>20.2</td>
<td>49.2</td>
</tr>
<tr>
<td>Delayed Policy (20 years)</td>
<td>14.9</td>
<td>34.1</td>
</tr>
<tr>
<td>Tax only</td>
<td>20.2</td>
<td>49.2</td>
</tr>
<tr>
<td>Subsidy only</td>
<td>6.2</td>
<td>12.4</td>
</tr>
</tbody>
</table>

*Note: The optimal policy increases welfare by 20.2% compared to laissez-faire, in the GHKT damages case.*

<table>
<thead>
<tr>
<th>Welfare compared to optimal policy, in percentage points</th>
<th>GKHT damages</th>
<th>High damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Policy</td>
<td><em>reference</em></td>
<td><em>reference</em></td>
</tr>
<tr>
<td>Delayed Policy (20 years)</td>
<td>-3.7</td>
<td>-8.5</td>
</tr>
<tr>
<td>Tax only</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Subsidy only</td>
<td>-10.4</td>
<td>-21.1</td>
</tr>
</tbody>
</table>

*Note: The delayed policy reduces welfare by 3.7% compared to the optimal policy, in the GHKT damages case.*
## Welfare effects with 1% discount rate

<table>
<thead>
<tr>
<th>Welfare compared to laissez-faire, in percentage points</th>
<th>GKHT damages</th>
<th>High damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Policy</td>
<td>30.4</td>
<td>77.8</td>
</tr>
<tr>
<td>Delayed Policy (20 years)</td>
<td>24.0</td>
<td>57.2</td>
</tr>
<tr>
<td>Tax only</td>
<td>30.5</td>
<td>77.8</td>
</tr>
<tr>
<td>Subsidy only</td>
<td>11.1</td>
<td>22.3</td>
</tr>
</tbody>
</table>

*Note: The optimal policy increases welfare by 30.4% compared to laissez-faire, in the GHKT damages case.*

<table>
<thead>
<tr>
<th>Welfare compared to optimal policy, in percentage points</th>
<th>GKHT damages</th>
<th>High damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Policy</td>
<td>Reference</td>
<td>Reference</td>
</tr>
<tr>
<td>Delayed Policy (20 years)</td>
<td>-4.4</td>
<td>-9.0</td>
</tr>
<tr>
<td>Tax only</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Subsidy only</td>
<td>-13.3</td>
<td>-25.3</td>
</tr>
</tbody>
</table>

*Note: The delayed policy reduces welfare by 4.4% compared to the optimal policy, in the GHKT damages case.*
Conclusion

• Innovation-based climate models suggest that action must be taken urgently and that multiple instruments should be used

• Our calibration confirms the delay cost but so far we find no big loss from using carbon tax only when taking shale gas boom as given

• Yet recall that green research subsidies help mitigate the negative long-run effects of shale gas boom
Conclusion

- The role for green industrial policy (Aghion, Hemous, Liu)
  - We consider the green / energy transition along the value chain in the presence of Pigovian taxation.
  - Complementarities across sectors can lead to multiple equilibria where either clean technologies are adopted along the value chain or where they are not adopted.
  - This speaks to the role of industrial policy to coordinate the clean transition.
  - With a pigovian tax alone, to remove multiplicity then one would need too large of a tax!
Extra slide
– GKHT damages (from Golosov, Krusell, Hassler, Tsyvinsky, 2014)
  • \( v(S_t) \sim 1 - e^{-\gamma_D(S_t-S_0)} \) where \( S \) is the quantity of CO2 in the atmosphere
  • \( \gamma_D = 1.1 \times 10^{-4} \)

– High damages
  • Increase parameter \( \gamma_D \) to double the projected effects of unmitigated end-of-century warming