Transition to Green Technology along the Supply Chain

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Motivation

- Green transition requires switching from fossil fuels to cleaner energy sources **along the production chain**:
  - e.g., gasoline cars $\rightarrow$ electric vehicles: require batteries, which are also emissions intensive
- Broad consensus worldwide on need to speed up transition; but countries diverge on how to achieve the goal
  - Europe: Carbon tax, cap-and-trade; US: industrial policy (e.g., Inflation Reduction Act)
- This paper: a dynamic model of technological transition along the supply chain

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Strategic complementarity, reminiscent of Big-Push, but ***cross-sector along the supply chain*** $\Rightarrow$ new insights

1. Multiple steady-states but a unique equilibrium
2. The social optimum requires both a carbon tax and targeted subsidies
3. Small and temporary sectoral subsidies ("small nudges") to key sectors can have large long-run effects
4. If subsidies are limited, there is a network argument to start downstream
5. With suboptimal carbon prices, excess electrification can be a second best policy.
6. Misdirected industrial policy can permanently derail the green transition

Literature

- Macroeconomics of climate change:
  - IAMs: Nordhaus (1994), Golosov, Hassler, Krusell, and Tsyvinski (2014), ...
  - DTC literature: Acemoglu, Aghion, Bursztyn, and Hémous (2012), Acemoglu, Akcigit, Hanley, Kerr (2016), ...
  - Static production networks: King, Tarbush and Teytelboym (2019), Devulder and Lisack (2020), ...
- Strategic complementarities in technology adoption:
  - Murphy, Shleifer, and Vishny, (1989), Sturm (2023), ...
  - In an environmental context: Greaker and Midttømme (2016), Dugoua and Dumas (2021).
  - Novelty here: dynamic model with a unique equilibrium but multiple steady states (see also Crouzet, Gupta, and Mezzanotti, 2023).
- Industrial policy:
  - Big push (Murphy, Shleifer, and Vishny, 1989), Infant industry (Greenwald and Stiglitz , 2006),
  - Knowledge externalities: Liu (2019), Liu and Ma (2023), Donald (2023), Buera and Trachter (2024)

Baseline model: economic environment

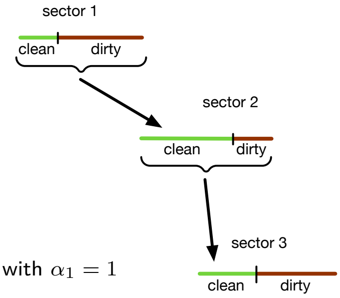
- Discrete time; representative households with preferences

$$U = \sum_{t=0}^{\infty} \beta^t \left(\ln c_t - \ell_t - \underbrace{a_t}_{\text{disutil. from emissions}} \right)$$

- Clean production is a vertical supply chain with N layers

$$\ln y_{it} = \int_0^1 \ln y_{it}(\nu)\, \mathrm{d}\nu,$$

$$y_{it}(\nu) = \underbrace{\ell_{dit}(\nu)}_{\text{dirty process}} + \mathbf{1}_{\text{greenified}}(\nu) \underbrace{\left(\frac{e^z \ell_{cit}(\nu)}{\alpha_i} \right)^{\alpha_i} \left(\frac{m_{it}(\nu)}{1-\alpha_i} \right)^{1-\alpha_i}}_{\text{clean process}}, \text{ with } \alpha_1 = 1$$



- Adopting the clean technology ("greenify") requires a one-time cost $\phi_i(\nu)$, with CDF $F_i(\cdot)$

- Disutility from emissions is proportional to ($\xi\times$) the use of labor in dirty production process

- Key assumption: clean supply chain does not benefit dirty production (i.e., gas engines do not use batteries)
  - (But there could be a complex fully dirty chain).

Market structure and markups

- Dirty production is competitive
  - government may impose a carbon tax τ; Pigouvian tax sets $\tau = \xi$, disutility of emissions

- If a producer pays the cost to transition: one-period monopoly, Bertrand-competes with dirty producers
  - after one period, clean production is also competitive
  - assume that given carbon tax, clean production is cheaper; let $Z \equiv z + \ln(1+\tau)$ be its tax-inclusive cost advantage

- Key state variables are the shares of varieties that have been greenified in each sector: $\{\chi_{it}\}_{i=1}^{N}$

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- Producer of a newly transitioned variety charges a mark-up:

$$\theta_{i,t} = e^{Z\mu_{it-1}},$$

  - μ_{it} is the network-adjusted share of clean content when producing a clean variety in sector i:

$$\mu_{1t} = 1 \quad \text{and} \quad \mu_{it} = \alpha_i + (1-\alpha_i)\,\chi_{i-1,t}\mu_{i-1,t}.$$

  - more greenification upstream ($\mu_{i,t-1} \nearrow$) $\implies$ higher mark-up for newly transitioned varieties

Revenues, profits, and incentives to adopt the clean technology

- Revenue of a variety in the most downstream sector is $r_{Nt} = 1$ (given normalization). For all $i < N$,

$$r_{it} = \underbrace{(1 - \alpha_{i+1})\,\widetilde{\chi}_{i+1,t}}_{\text{input cost share in } i+1} r_{i+1,t}, \qquad \widetilde{\chi}_{i+1,t} \equiv \underbrace{\chi_{i+1,t-1}}_{\text{already elec.}} + \underbrace{(\chi_{i+1,t} - \chi_{i+1,t-1})\, e^{-Z\mu_{i+1,t-1}}}_{\text{newly elec.}}$$

- By induction, revenues increase with the cost share of clean varieties downstream ($j > i$)

$$r_{it} = \prod_{j=i+1}^{N} [\widetilde{\chi}_{jt}(1 - \alpha_j)]$$

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- Profits for a newly transitioned variety in sector i are given by:

$$\pi_{it} = \left(1 - e^{-Z\mu_{i,t-1}}\right) \prod_{j=i+1}^{N} \widetilde{\chi}_{jt}\,(1-\alpha_j)$$

  - producers greenify additional varieties if and only if $\pi_{it} > \phi_i(\nu) \implies \chi_{it} = F_i(\pi_{it})$

- Upstream greenification affects sector i with a delay through an input cost effect (in $\mu_{i,t-1}$)
- Downstream greenification affects sector i contemporaneously through a market size effect (in $\widetilde{\chi}_{jt}$)

Equilibrium dynamics and steady-state

- The law of motion for $\{\chi_{it}\}$ is then given by: $\chi_{it} = \max\{\chi_{i,t-1},\ F_i(\pi_{it})\}$
- In a steady-state, $\{\chi_i\}$ is time-invariant

Proposition 1. For given carbon tax τ, generically there may exist multiple steady-states whenever $N \geq 2$.

- Low $\{\chi_i\}$ in downstream $\implies$ low demand for upstream inputs $\implies$ low $\{\chi_i\}$ in upstream
- Low $\{\chi_i\}$ in upstream $\implies$ low cost advantage for downstream production $\implies$ low $\{\chi_i\}$ in downstream

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Proposition 2. Given initial condition $\{\chi_{i0}\}_{i=1}^{N}$, the economy features a unique equilibrium path $\{\chi_{it}\}_{t>0}$.

- Intuition: greenification creates additional demand contemporaneously but reduces input costs with a delay

Social planner (1)

- Social planner solves

$$\max_{c_t, \ell_{dit}, \ell_{cit}, \chi_{i,t}} \sum_{t=0}^{\infty} \beta^t \left(\ln y_{Nt} - (1+\xi) \sum_i \ell_{dit} - \sum_i \ell_{cit} - \sum_i \int_{\chi_{i,t-1}}^{\chi_{i,t}} \phi_i(s)\, ds \right).$$

  - All electrification happens immediately in the optimum => immediate steady-state.
  - With a Pigouvian tax $\tau = \xi$, labor allocation for given χ_i is optimal in steady-state,
  - and problem amounts to choosing the correct technology levels $\{\chi_i\}$.

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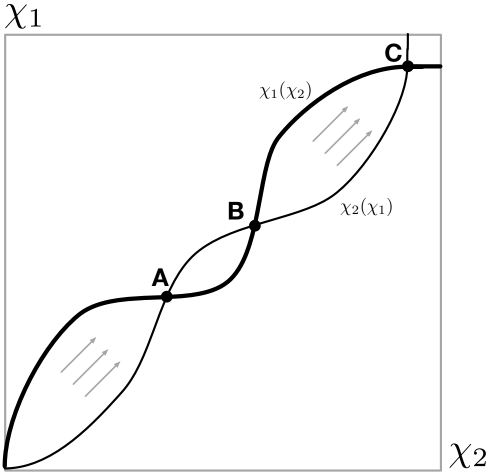
  - and problem amounts to choosing the correct technology levels $\{\chi_i\}$.
- Given Pigouvian tax, decentralized incentives in steady-state still differ from the planner's in 3 ways:

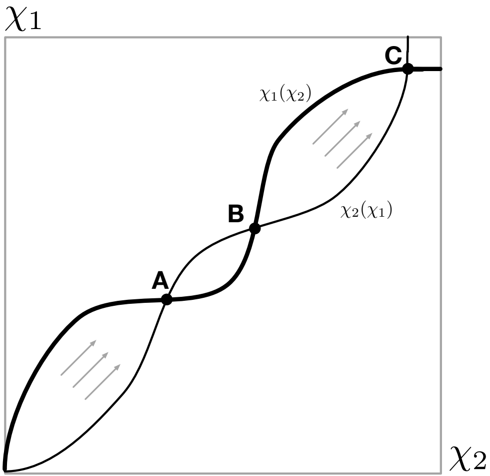
$$\underbrace{\chi_i = F_i\left(\left(1 - e^{-\mu_i, Z}\right) \prod_{j=i+1}^{N} \chi_j (1-\alpha_j)\right)}_{\text{decentralized correspondence}}, \qquad \underbrace{\chi_i = F_i\left(\frac{\mu_i Z}{1-\beta} \prod_{j=i+1}^{N} \chi_j (1-\alpha_j)\right)}_{\text{planner's FOC with respect to } \chi}$$

  - 1) time horizon difference (call for a uniform subsidy)
  - 2) profit vs. consumer surplus from electrification (but if Z is small, $1 - e^{-\mu_i, Z} \approx \mu_i Z$)
  - 3) there exist multiple steady-states due to strategic complementarity.

Social planner (2)

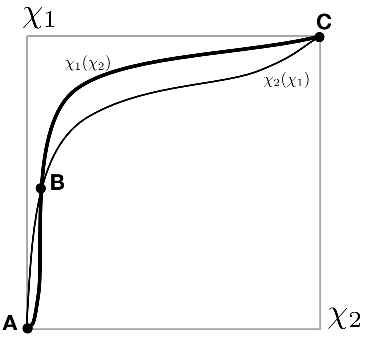


Social planner (2)



Proposition 3. (1) The optimal *steady-state* can be uniquely implemented through a carbon price together with a whole set of time-varying sector specific subsidies for adopting the clean technology.
(2) Generically, carbon tax + uniform (i.e. untargeted) clean subsidy cannot implement the optimal SS.

Limited subsidies can make a big difference



- Example with two layers and three SS: no greenification (A), full greenification (C), and in-between (B)
  - a small and temporary subsidy, to the "key" sector ($\chi_2 > \chi_2^B$), can kick-start the economy from the no-greenification SS (A) to a little beyond the unstable "in-between" greenification steady-state (B)
  - thereafter, on its own the economy will move towards the full-greenification steady-state
- **Implication:** a small, targeted nudge may be sufficiently effective; "big push" is not needed

Which sector to target? Propagation of adoption incentives in steady-state

- Imagine that the government is constrained to conduct local intervention ($\mathrm{d} \ln \chi$) in at most one sector. Should it target a downstream or an upstream sector?

Which sector to target? Propagation of adoption incentives in steady-state

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Proposition 4. (a) An increase in greenification downstream raises incentive one-for-one:

$$\frac{\partial \ln \pi_i}{\partial \ln \chi_k} = 1 \textbf{ if } k > i.$$

(b) An increase in greenification upstream raises incentive less-than-one-for-one:

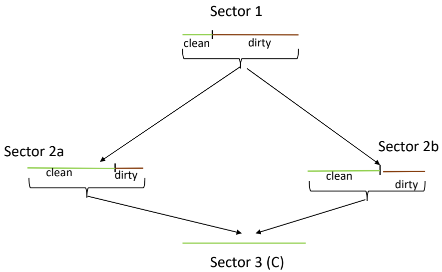
$$\frac{\partial \ln \pi_i}{\partial \ln \chi_k} = \frac{\mu_i Z e^{-\mu_i Z}}{1 - e^{-\mu_i Z}} \frac{\left(\prod_{j=0}^{i-k-1}(1-\alpha_{i-j})\chi_{i-j-1}\right)\mu_k}{\mu_i} < 1 \textbf{ if } k < i.$$

(c) Incentives propagated from upstream relies on greenification along the chain:

$\partial \ln \pi_i / \partial \ln \chi_k \to 0$ **if** $\chi_j \to 0$ **for any** j **such that** $k \leq j < i$**.**

- Intuition: the upstream good is not the only input for an greenified variety; labor is the other input
  - hence only partial pass-through of upstream costs to downstream profit share ($\frac{\mathrm{d}\ln\left(\alpha_i + (1-\alpha_i)\chi_{i-1}\right)}{\mathrm{d}\ln\chi_{i-1}} < 1$)
- **Implication**: when initial $\{\chi_i\}$ is low, the planner should always target downstream (provided that the relative marginal cost of greenification is bounded across sectors)
- Also, downstream intervention immediately propagates; upstream intervention propagates with a delay

Generalization: 2 downstream sectors

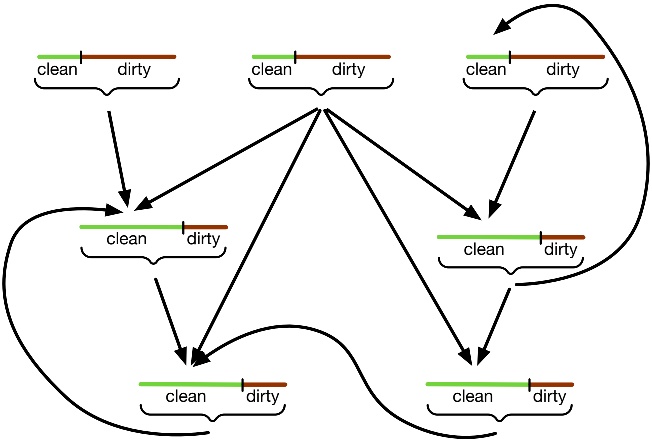


- Sectors $2a$ and $2b$ have the same labor share α and β_a, β_b denote their final consumption shares.
- Cross-sectoral effects of electrification on electrification incentives:

$$\frac{\partial \ln \pi_1}{\partial \ln \chi_{2k}} = \frac{\chi_{2k}\beta_k}{\chi_{2a}\beta_a + \chi_{2b}\beta_b} \text{ and } \frac{\partial \ln \pi_{2k}}{\partial \ln \chi_1} = \frac{\mu_2 Z e^{-\mu_2 Z}}{1 - e^{-\mu_2 Z}} \frac{\chi_1 (1-\alpha)}{\alpha + \chi_1 (1-\alpha)}.$$

- For low χ, targeting downstream sectors has a bigger effect on electrification incentives than targeting the upstream sector.
  - This need not be true when χ_1 is far from 0 (think for example of electricity as sector 1).

Generalization beyond a vertical chain: clean production may use any inputs



- Next: generalize the steady-state formula for how greenification incentives propagate in the network
  - if the network is acyclic, then equilibrium is unique (SS characterization does not rely on unique eqm.)

Generalization beyond a vertical chain: clean production may use any inputs

- In steady-state, profit rent from greenification of a new variety in sector i:

$$\pi_i(\nu) = \underbrace{\left(1 - e^{-Z\mu_i}\right)}_{\text{profit margin}} \underbrace{r_i}_{\text{revenue}} \Rightarrow \left[\frac{\mathrm{d}\ln \pi_{ii}}{\mathrm{d}\ln \chi_k}\right] = Diag\left(\frac{Ze^{-\mu_i Z}}{1 - e^{-\mu_i Z}}\right)\left[\frac{\mathrm{d}\mu_i}{\mathrm{d}\ln \chi_k}\right] + \left[\frac{\mathrm{d}\ln r_i}{\mathrm{d}\ln \chi_k}\right]$$

- Profit margin depends on the greenification of one's supplier, supplier's supplier, and so on

$$\left[\frac{\mathrm{d}\mu_i}{\mathrm{d}\ln \chi_k}\right] = \left(\hat{\boldsymbol{\Sigma}}^{\chi} + \left(\hat{\boldsymbol{\Sigma}}^{\chi}\right)^2 + \cdots\right) Diag\left(\boldsymbol{\mu}\right)$$

  - $\hat{\boldsymbol{\Sigma}}^{\chi}_{ik}$ is sector i's cost share on green inputs from sector k

- Revenue depends on the greenification of one's customer, customer's customer, and so on

$$\left[\frac{\mathrm{d}\ln r_i}{\mathrm{d}\ln \chi_k}\right] = \left(\boldsymbol{\Omega} + \boldsymbol{\Omega}^2 + \cdots\right)$$

  - $\boldsymbol{\Omega}_{ik}$ is the fraction of sector i's revenue earned by selling to k

- In steady-state, incentives from downstream propagate one-for-one (each row of $\boldsymbol{\Omega}$ sums to one)
  - from upstream: propagate less than one-for-one; moreover, limited by the "weakest link" (row-sum of $\hat{\boldsymbol{\Sigma}}^{\chi}$ <1, goes to zero as $\chi_k \to 0 \forall k$)

Underpriced emissions: industrial policy as a second best

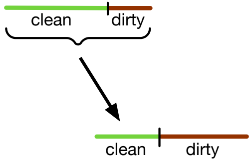
- So far, industrial policy is a complement to carbon pricing. But often, carbon is underpriced: $\tau < \xi$.
- How would a social planner use industrial policy as a second best solution?
  - We consider a steady-state (social planner can remove the monopoly distortion)

Proposition 5. In the absence of a Pigouvian carbon price, optimal greenfication satisfies

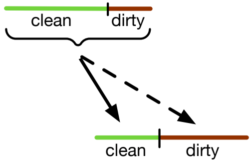
$$\chi_i = F_i\left(\frac{\ln\left(\left(1+\tau\right)e^{z}\right)}{1-\beta}\mu_i \prod_{j>i}\left[\chi_j\left(1-\alpha_j\right)\right] + \frac{\xi-\tau}{1-\beta}\left(-\frac{\partial \ell_d}{\partial \chi_i}\right)\right).$$

- Greenification is distorted so as to greenify more sectors whose emissions depend more on greenification.
- Interestingly, in a vertical supply chain $\frac{\partial \ell_d}{\partial \chi_i}$ tends to be larger for downstream sectors, particularly when electrification is low.
  - Complementarity in emission reductions: greenification in each sector is more effective when the others are more electrified...
  - ... but this complementarity is asymmetric as the effect of upstream greenification on emissions vanishes if greenification downstream is low.

Generalization: use of clean vertical chain by the dirty sector

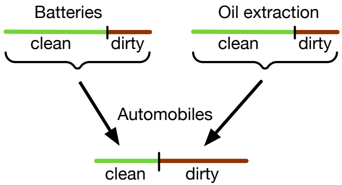


- So far, we have assumed only inputs to clean production can be greenified



- Qualitative insights go through if dirty technology uses the same inputs but less intensively
  - so that greenification remains strategically complementary across sectors

Strategic substitutability: misguided policy can permanently derail the green transition



- Suppose there are two upstream sectors: oil extraction (for gasoline cars) and batteries (for electric cars)
  - strategic complementarity between batteries and electric cars
  - strategic substitutability between oil extraction and {batteries, electric cars}

- Two implications
  1. Industrial policy that favors oil extraction can backfire and halt the transition that would have otherwise occurred in electric cars without government intervention, thereby reducing long-term welfare
     - an additional rationale to target downstream sectors (electric cars)
  2. Laissez-faire may feature excess greenification in oil extraction compared to the ex ante social optimum

Conclusion

- A parsimonious model of dynamic green transition along the supply chain
  - features strategic complementarity, reminiscent of Big-Push, but *cross-sector along the supply chain*
  - a minimal model: no production distortion in steady-state
  - isolate the inefficiency and coordination in the adoption of green technology

- New insights:
  1. Multiple steady-states but a unique equilibrium
  2. The social optimum requires both a carbon tax and targeted subsidies
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  4. If subsidies are limited, there is a network argument to start downstream
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In progress: a simple calibration based on hydrogen in heavy-duty transport.

Appendix: Iron and steel (1)

- Focus on global iron and steel production (7-9% of total CO2 emissions).
  - To achieve high-quality zero-emission steel, need to switch from fossil-fuels to hydrogen.
  - But hydrogen itself can be produced in a dirty way (using methane) or a clean way (using water).
- Consider $N = 2$, sector 2 is steel and sector 1 is hydrogen:
  - Map the innovation costs with the excess initial vs n-th of a kind clean levelized costs.
  - Map n-th of a kind cost to the productivity shifter z.
  - Map the distribution of innovation costs $\phi_1(\chi_1)$ to the distribution of excess initial vs. n-th of a kind clean hydrogen across countries.
  - Allow for heterogeneity in the relative input efficiency parameter z_i, the emission rate ξ_i, and a TFP parameters A_i.
  - Consider an uniform carbon tax in USD.

Appendix: Iron and steel (2)

- At \$25/tCO2: 3 stable steady-states, (0%, 0%), (59%, 54%), and (82%, 84%).
  - Diff. in emissions between (0%, 0%) and (82%, 84%) s.s. = 2.4 billion tons of CO2 per year (close to total EU emissions).
  - At \$12.5/tCO2: 1 stable s.s. (0%, 0%). At \$100/tCO2, 1 stable s.s. (100%, 100%).