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 → 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: cap-and-trade; US, China: industrial policy (e.g., Inflation Reduction Act)
- This paper: a dynamic model of technological transition along the supply chain.
  - We show that coordination along the supply chain provides a new rationale for industrial policy (*on top of* carbon pricing).

Framework

- We model a "green supply chain".
- In each layer production can be produced in a dirty way using labor (and fossil fuels) or in a clean way using labor and the upstream input.
    - Clean production process is only available upon an "electrification" innovation;
    - Pigovian environmental tax ⇒ Clean production process is cheaper than the dirty one.
- Incentives to "electrify" travel both downstream and upstream:
    - Upstream: market size effect;
    - With a delay, downstream: input cost effect.
- Electrification across sectors is strategic complement, which generates a coordination problem.

Main results

- **Strategic complementary**, as in Big-Push, but **cross-sector along the supply chain** $\Longrightarrow$ several new insights
  - 1) Our economy features a unique equilibrium but generally multiple steady-states;
  - 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, they should primarily target downstream sectors; doing so leads to larger multipliers;
  - 5) (In an extended model with electrification for inputs to dirty production) Misdirected industrial policy can permanently derail the green transition.
- Lessons from the model extend to other technology 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).

Outline

Model and equilibrium

Social planner problem

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A Quantitative example

Conclusions

Consumption

- Discrete time.
- Representative households with preferences

$$U = \sum_{t=0}^{\infty} \beta^t \left(\ln c_t - \ell_t - a_t \right)$$

  - c_t is consumption, ℓ_t is labor supply, a_t is disutility of pollution, and β is the discount factor.
  - Normalization: $w_t = 1 \Rightarrow p_t c_t = 1$ with p_t is the price index.

Production (1)

- Production is a vertical supply chain with N layers:
  - Each sector is a Cobb-Douglas aggregate of a continuum of varieties:

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

    - $i = 1$ most upstream and $i = N$ most downstream: $c_t = y_{Nt}$.
- We model a green supply chain:

$$y_{it}(\nu) = \ell_{dit}(\nu) + \gamma(\nu)\left(\frac{e^z \ell_{cit}(\nu)}{\alpha_i}\right)^{\alpha_i}\left(\frac{m_{it}(\nu)}{1-\alpha_i}\right)^{1-\alpha_i} \text{ with } \alpha_1 = 1,$$

  - $\gamma(\nu) = 1$ for electrified varieties, $\gamma(\nu) = 0$ otherwise.
  - $m_{it}(\nu)$ intermediate input from sector $i-1$ used by the clean process.
  - e^z is a productivity shifter (z positive or negative).

Production (2)

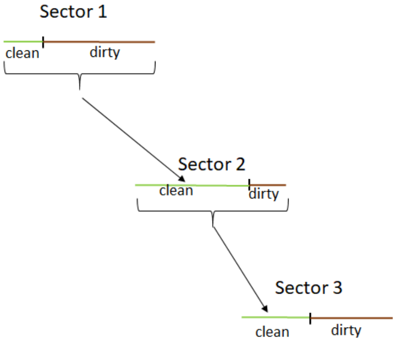

Figure: Example with $N = 3$

- Key assumption: clean supply chain does not benefit dirty production (i.e., gas engines do not use batteries)
  - Dirty can have a complex supply chain on its own – if fully dirty.
  - Extension: add clean innovation for dirty production.

Emissions and carbon tax

- Disutility from emissions is proportional to the use of labor in dirty production process: $a_t = \xi \ell_{dt}$.
  - Government imposes a tax τ_t on dirty production.
  - Equivalent to a fossil fuel resource used in Leontieff way with labor,
  - τ_t and a_t can include extraction costs.
- Electrified varieties in sector i use the clean production process whenever

$$e^{-\alpha_i z} p_{i-1,t}^{1-\alpha_i} < 1 + \tau_t.$$

  - Define $Z = z + \ln(1+\tau)$, the (tax-inclusive) cost advantage of clean production,
  - Assume $Z > 0$: clean production is always preferred when available.

Electrification and market power

- Key state variables: shares of electrified varieties: $\{\chi_{it}\}_{i=1}^{N}$.
- Electrification requires a one-time cost $\phi_i(\nu)$, with CDF $F_i(\cdot)$.
- Every period, a single firm may pay the innovation cost and electrify.
  - The firm obtains a monopoly for 1 period and Bertrand competes with dirty producers.
  - After 1 period, clean production is competitive.
- Dirty production process is operated competitively.

Mark-ups

- Producers of newly electrified variety charges a mark-up:

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

  - μ_{it} is the network-adjusted share of electrified content when producing an electrified 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 electrification upstream ($\mu_{i,t-1} \nearrow$) $\implies$ higher mark-up for newly electrified varieties.

Revenues and profits

- Revenue of a variety in the most downstream sector is $r_{Nt} = 1$.
- For $i < N$, sector $i < N$ sells to clean producers in $i+1$. Revenues are:

$$\begin{aligned} r_{it} &= (1-\alpha_{i+1}) \left[\underbrace{\chi_{i+1,t-1}}_{\text{already elec.}} + \underbrace{\left(\chi_{i+1,t} - \chi_{i+1,t-1}\right) e^{-Z\mu_{i+1,t-1}}}_{\text{newly elec.}} \right] r_{i+1,t} \\ &= (1-\alpha_{i+1})\, \widetilde{\chi}_{i+1,t} r_{i+1,t} \end{aligned}$$

- By induction, revenues increase with the cost share of electrified varieties downstream

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

- Profits from electrification for any variety producer in sector i are:

$$\pi_{it} = (1-\theta_{it}^{-1}) r_{it} = \underbrace{\left(1 - e^{-Z\mu_{i,t-1}}\right)}_{\substack{\text{depends on upstream} \\ \text{electrification with a delay}}} \underbrace{\textstyle\prod_{j=i+1}^{N} \widetilde{\chi}_{jt}(1-\alpha_j)}_{\substack{\text{depends on contemporaneous} \\ \text{downstream electrification}}}.$$

  - Producers electrify additional varieties if and only if $\pi_{it} > \phi_i(\nu)$.

Equilibrium dynamics

- The law of motion for $\{\chi_{it}\}$ is then given by:

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

Proposition

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

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

Steady-state(s)

- In a steady-state, $\{\chi_i\}$ is constant. Steady-states are characterized by:

$$\chi_i = F_i\left(\left(1 - e^{-\mu_i, Z}\right)\prod_{j=i+1}^{N}\left(\chi_j(1-\alpha_j)\right)\right). \tag{1}$$

$$\text{and } \mu_1 = 1, \quad \mu_i = \alpha_i + \chi_{i-1}\mu_{i-1}(1-\alpha_i).$$

  - (Technically (1) may only be an inequality ($\geq$) — but we ignore that case as it requires starting with a value for χ_i that is too high).

Proposition

For given carbon tax τ, there exist multiple steady-states over a non-empty open set of parameters whenever $N \geq 2$.

- Low $\{\chi_i\}$ in downstream $\Longrightarrow$ low demand for upstream inputs $\Longrightarrow$ low $\{\chi_i\}$ in upstream.
- Low $\{\chi_i\}$ in upstream $\Longrightarrow$ low cost advantage for downstream production $\Longrightarrow$ low $\{\chi_i\}$ in downstream.
- This also holds with cap-and-trade instead of a carbon tax.

Outline

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Social planner solution

- 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 $\{\chi_i\}$.

Comparing decentralized steady-state vs social planner

$$\underbrace{\chi_i = F_i\Big(\left(1 - e^{-\mu_i, Z}\right) \prod_{j=i+1}^{N} \chi_j \left(1-\alpha_j\right)\Big)}_{\text{decentralized correspondence}}, \tag{2}$$

$$\underbrace{\chi_i = F_i\Big(\tfrac{\mu_i Z}{1-\beta} \prod_{j=i+1}^{N} \chi_j \left(1-\alpha_j\right)\Big)}_{\text{planner's FOC with respect to } \chi}. \tag{3}$$

- Given Pigouvian tax, decentralized incentives in steady-state still differ from the planner's in 3 ways:
    - 1) time horizon difference (call for a uniform subsidy)
    - 2) profit vs. consumer surplus from electrification (but if Z is small, $1 - e^{-\mu_i, Z} \approx \mu_i Z$)
    - Most importantly 3) there exist multiple steady-states due to strategic complementarity and (3) does not uniquely identify the optimum!

Steady-states Multiplicity

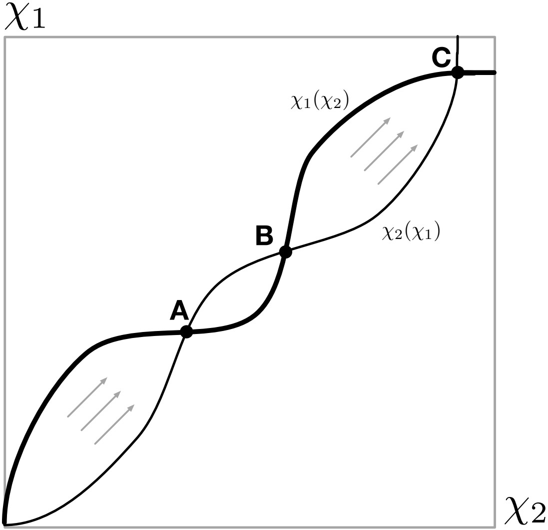

Figure: Multiple steady-states

Implementing the steady-state social optimum

Proposition

The optimal steady-state can be uniquely implemented through a carbon price together with a whole set of time-varying sector specific subsidies.

- Assume that the social planner imposes a Pigouvian tax $\tau_i = \xi$, and a set of sector specific subsidies $\{q_{i,t}\}$.
- The equilibrium level of electrification at time t is uniquely determined by

$$\chi_{i,t} = F_i \left(\frac{\left(1 - \left[e^z \left(1 + \xi\right)\right]^{-\mu_{i,t-1}}\right)}{1 - q_{i,t}} \prod_{j=i+1}^{N} \left(\widetilde{\chi}_{j,t}(1 - \alpha_j)\right) \right),$$

- By choosing the appropriate $q_{i,t}$, it is possible to implement the optimum χ_i^{SP} immediately.
  - This economy differs from the optimum in the first period.

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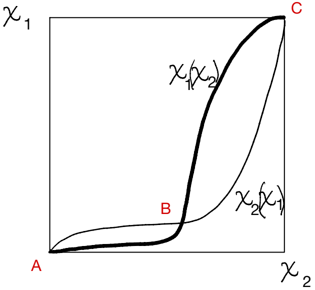
Limited subsidies can make a big difference



- Ex. with $N = 2$ and 3 steady-states: no electrification (A), full electrification (C), and interior (B)
  - a small and temporary subsidy to the "key" sector ($\chi_2 > \chi_2^B$) can kick-start the economy from the no-electrification steady-state (A) to a little beyond the unstable interior steady-state (B)
  - thereafter, the economy will move on its own toward the full-electrification steady-state
- **Implication:** a small, targeted nudge may be sufficiently effective; "big push" is not needed.

Target downstream (esp. if electrification is low) (1)

- Assume government is constrained to act in few sectors, which sector should it target?

Proposition

(a) An increase in electrification downstream raises incentives one-for-one:

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

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

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

(c) Incentives propagated from upstream relies on electrification along the chain: $\partial \ln \pi_i / \partial \ln \chi_k \to 0$ *if* $\chi_j \to 0$ *for any* j *such that* $k \leq j < i$.

Target downstream (esp. if electrification is low) (2)

- Intuition: the upstream good is not the only input for an electrified variety; labor is the other input
  - hence only partial pass-through of upstream costs to downstream profit share.
- **Implication**: when initial $\{\chi_i\}$ is low, the planner should always target downstream.
  - $+$ downstream intervention immediately propagates; upstream propagates with a delay.

Multiple downstream sectors

- Assume 2 layers but with with 2 downstream sectors ($2a$ and $2b$) with consumption shares β_a and β_b.
    - ◦ Same upstream sector with the same cost share $1-\alpha$.
- Steady-state is characterized by

$$\chi_1 = F_1\left(\left(1-e^{-Z}\right)(1-\alpha)\left(\beta_a\chi_{2a}+\beta_b\chi_{2b}\right)\right). \tag{4}$$

$$\chi_{2k} = F_{2k}\left(\left(1-e^{-\mu_2 Z}\right)\beta_{2k}\right) \text{ with } \mu_2{=}\alpha{+}\chi_1(1-\alpha). \tag{5}$$

- 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.

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A model with strategic substitutability

- $N = 2$, but with two upstream sectors $1a$ is an input for the dirty process and $1b$ for the clean process.
  - Sector 2 still prefers using the clean input when available.

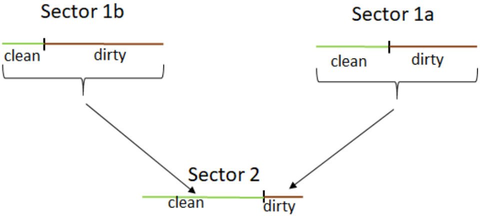


Figure: Strategic substitutability model

Steady-states

- Steady-states are characterized by:

$$\chi_{1a} = F_{1a}\left(\left(1 - e^{-Z}\right)(1 - \chi_2)(1 - \alpha)\right)$$

$$\chi_{1b} = F_{1b}\left(\left(1 - e^{-Z}\right)\chi_2(1 - \alpha)\right)$$

$$\chi_2 = F_2\left(1 - e^{-Z\mu_2}\right) \text{ with } \mu_2 = \alpha - (1 - \alpha)\chi_{1a} + \chi_{1b}(1 - \alpha).$$

- Strategic complementarity between electrification in $1b$ and 2, but strategic substitutability with electrification in $1a$
- More generally:
  - If downstream clean and dirty both use sectors $1a$ and $1b$ equally: network does not matter.
  - If downstream clean uses both $1a$ and $1b$ more intensively than dirty: strategic complementarity (previous case).
  - If downstream clean uses more intensively one input and downstream dirty uses more intensively the other input: strategic substitutability (this case).

Consequences

- Industrial policy can backfire:
  - We build an example where in laissez-faire the economy converges toward full electrification in sectors 2 and $1b$;
  - but to "accelerate" the transition, the government subsidizes electrification in sector $1a$;
  - this decreases the incentives to electrify in sectors 2 and $1b$ and the economy is stuck in another steady-state with no electrification in 2 and $1b$.
  - Welfare is lower than without the industrial policy.
- Target downstream: subsidies to the downstream sector do not backfire.
- Laissez-faire may feature excess electrification in some sectors.

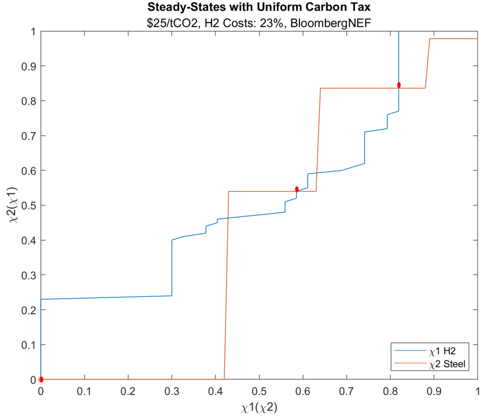
Outline

Iron and steel

- 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. details

Results for baseline parameters

- 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%).



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Conclusions

Conclusion and next steps

- We analyzed a model of green technological transition along a supply chain:
    - We showed that there are strategic complementarities for green innovation across sectors leading to multiple steady-states;
    - This provides a rational for targeted industrial policy.
    - Though (in an extension of the model), we also saw that industrial policy could backfired.
    - At low level of electrification, it is better to target downstream.
- Our analysis in this paper could be extended in several interesting directions:
    - Quantitative macro model of the full network.
    - Considering international value chains.
    - Use the framework to think about the elasticity of substitution between clean and dirty technologies.

Parameterization (1)

- Hydrogen:
  - Calibrate the relative input efficiency parameter z_1 to the ratio of production costs for future clean hydrogen and dirty hydrogen from BloombergNEF (2023), yielding $z_1 = 0.7608$.
  - Distribution of innovation costs $\phi_1(\chi_1)$ range from \$0.78/kgH2 in China to more than \$4/kgH2.
  - TFP parameter A_1 set to match levelized costs of steel production.
  - Calibrate the emission intensity to the 2021 global average of 12.5kgCO2/kgH2 (IEA 2023).
- H_2 is used for other applications than steel: model overestimates the fixed innovation costs relative to benefits.
  - Projected demand share of steel for H_2in 2050 is 23%. We adjust fixed costs accordingly.

Parameterization (2)

- For the steel sector, use BloombergNEF (2021):
    - Estimate hydrogen cost share in clean steel, leading to $\alpha_2 = 0.86$.
    - Use the relative costs of dirty (\$544/tS) vs n-th of a kind clean (\$489/tS) steel to calibrate $z_2 = 0.1239$.
    - TFP parameter A_2 to match total revenues in 2021 of \$1.034 trillion.
    - Emission intensity of dirty steel production to 2.2tCO2/ton steel.

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