Are Renewable Energy Policies Climate Friendly? 
The Role of Capacity Constraints and Market Power

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Motivation

Government support for renewable energies
1. Direct subsidy, mandatory blending, feed-in tariff, R&D support, etc.
2. Motivation: Global climate change; energy security; high (and uncertain) energy prices
3. Justifications: help substitute for fossil fuel use; distributed generation (low startup cost); smart grid (future of energy).

Can be controversial
1. Debate on biofuel: life cycle analysis, indirect land use change due to price effects. (Searchinger et al, 2008; Hertel et al 2010)
2. Emission impacts of electric cars (Zivin et al, 2013)
Key question: can renewable energies reduce GHG emissions?

- Impacts of biofuel on oil supply: rather limited in static models (Rajagopal et al, 2011; de Gorter and Drabik, 2011; Thompson et al, 2011)
  - Reason: small market share of biofuel in gasoline market
- Market share of solar is small in electricity market, so static price effect is low. (Mulder and Scholtens, 2013)
But dynamic aspect of impacts

- Fossil fuel is a dynamic business!
  1. Low price elasticity in the short run, but (delayed) high price elasticity in the long run through adjustments in drilling: responses to future prices and dynamic decision making
  2. Hydraulic fracturing (fracking) and horizontal drilling: more short-run responses

- Fossil fuel supply is *more responsive* to renewable energies when viewed from a dynamic perspective
  1. Simplest example: solar as backstop. No static response, big dynamic response
  2. General: much more elastic response than in a static model (Zhao, 2013)
Green Paradox

- Sinn (2008): dynamic effects can be counter-intuitive and opposite to static effects.
- Example: taxing carbon, improving energy efficiency
  1. Future fossil fuel price decreases: produce more now
  2. Story: dynamic impacts can be opposite to (predicted) “static” impacts
Dynamic is important for evaluating the impacts of renewable energies

- Global climate change is about the *time path* of carbon emissions rather than *levels*
  1. Extreme view: all or most carbon stored in fossil fuel will eventually be released
  2. GHG problem: carbon has been released *too fast*, far exceeding rates of dissipation
  3. GHG is a stock pollutant. Earlier emissions cause more NPV damage.
  4. Optimal path: lower emission *now*, implying higher emission in the future

- True Green Paradox should be about NPV of future damages, and can depend on damage functions (and adaptation) and discount rate.

- But literature takes simplified approach: delay extraction/emissions.
This paper

Question: what are the dynamic effects of renewable energy policies on fossil fuel supply?

- Dynamic impacts of renewable policies: sensitive to
  1. production capacity constraints of renewables
  2. market power in fossil fuel sector

- Capacity constraints: how much can be produced in a year?
  1. Resource limits: land availability, prime wind sites
  2. Government policy: US blend wall, China’s biofuel entry regulation (Chang et al 2012)

- Market power: somewhere between perfect competition and monopoly
  1. OPEC: cartel? oligopoly? Evidence of market power in recent oil price drop
  2. National oil companies: Russia, China, Venezuela
  3. This paper: two extremes (competition vs. monopoly). Companion paper studies cartel-fringe.
More accurate definition of Green Paradox

- Strict sense (strong Green Paradox): NPV of environmental damage increases.
- Literature: earlier exhaustion of fossil fuel (Grafton et al 2012); or higher current fossil fuel extraction - weak Green Paradox (Ploeg and Withagen 2012).
- This paper: combined condition - Green Paradox if and only if both conditions (increased current extraction and earlier exhaustion of resource).
Focus on dynamics - lots of abstraction: four substitutable energies

- Fossil fuels: nonrenewable, homogeneous (abstract from coal vs. natural gas vs. oil), high GHG emissions
- Two kinds of biofuels: subject to capacity constraint, lower GHG emissions
  1. Low cost biofuels: grain based ethanol. Currently competitive
Conceptual model (cont’d)

Renewable policies - synthesizing real world policies

- Subsidies (cost reduction): for biofuels and solar
- Capacity expansion for biofuels
  1. R&D that expands feedstocks
  2. Relaxation of restrictive policies.

Focus on: policies’ impacts on (i) supply paths of energies, and (ii) associated GHG paths (the latter the better).
Model setup

- Four substitutional energies: fossil fuels, low cost biofuels, high cost biofuels and solar.
  1. Unit production cost: \( c_f < c_{b,l} < p(0) < c_{b,h} < c_s \)
  2. Can extend to convex costs with similar results.

- Energy supply in period \( t \): \( q_f(t) \), \( q_{b,l}(t) \), \( q_{b,h}(t) \) and \( q_s(t) \).
  1. Capacity constraints: \( q_{b,l}(t) < \bar{q}_{b,l} \); \( q_{b,h}(t) < \bar{q}_{b,h} \);
  2. Restrictive enough that biofuels won’t drive out solar or fossil fuels.

- Renewable energy sectors are competitive.

- Stationary energy demand function \( p = h(Q) \)
Renewable energy supply rule

- Supply of biofuels, for $i = \{1, h\}$

$$q_{b,i}(t) \begin{cases} 
= 0, & \text{if } p(t) < c_{b,i} \\
\in [0, \bar{q}_{b,i}], & \text{if } p(t) = c_{b,i} \\
= \bar{q}_{b,i}, & \text{if } p(t) > c_{b,i}
\end{cases}$$

- Supply of solar

$$q_s(t) \begin{cases} 
= 0, & \text{if } p(t) < c_s \\
\in [0, h^{-1}(c_s) - \bar{q}_b - q_f(t)], & \text{if } p(t) = c_s
\end{cases}$$
Optimal supply of fossil fuels: perfect competition

- Optimization problem

$$\begin{align*}
\max_{\{q_f(t)\}} & \quad \int_0^\infty e^{-rt} [p(t) q_f(t) - c_f q_f(t)] \, dt \\
\text{s.t.} & \quad \dot{X}(t) = -q_f(t); \quad \int_0^\infty q_f(t) \, dt = X_0;
\end{align*}$$

1. $X(t)$: the reserve of fossil fuels at period $t$.
2. $X_0$: initial reserve.

- Solutions: Hotelling rule

$$h(q_f(t) + q_b(t) + q_s(t)) = c_f + \lambda e^{rt}$$

1. LHS: fossil fuel price $p(t)$.
2. RHS: augmented marginal cost, including Hotelling rent.
3. Hotelling rent increases at rate of interest (since no stock effects)
- $T_1$: high cost biofuels become available; fossil fuel supply drops by $\bar{q}_{b,h}$.
- Price is continuous, but $q_f(t)$ jumps at $T_1$.
- $T$: exhaustion time of fossil fuels.
Optimal fossil fuel supply: monopoly

- Cartel-fringe model: fossil fuel owner is Stackelberg leader.
- Optimization problem

\[
\begin{align*}
\max_{\{q_f(t)\}} \int_0^T e^{-rt} [h(Q(t)) q_f(t) - c_f q_f(t)] \, dt \\
\text{s.t.} \quad \dot{X}(t) = -q_f(t); \quad \int_0^T q_f(t) \, dt = X_0;
\end{align*}
\]

Supply rules of biofuels and solar

- Optimal condition: (residual) MR vs. augmented MC
  1. If interior solution:

\[
h'(Q(t)) q_f(t) + h(Q(t)) = c_f + \lambda e^{rt}
\]

  2. But possible corner solution: MR > AMC. Key condition driving important results.
monopoly supply path: staving-off period

- $T_1$: high cost biofuel: competitive but off market (stave-off: due to corner solution).
- $T_2$: high cost biofuels starts to supply the market;
- $T_3$: solar: competitive but off market;
- $T$: fossil fuels exhausted, solar starts to supply market
Policy analysis: effects of renewable policies

- Focus on GHG emission paths
- Climate friendly? Green Paradox? Complete evaluation needs info on
  1. Changes in supply paths due to policy
  2. Marginal damages over time
  3. Discount rate(s)
- Compromise (and more refined than Green Paradox literature):

**Definition:** A renewable energy policy is
- *climate friendly* if it both *reduces current fossil fuel supply* and *delays exhaustion time* of the fossil fuel.
- *subject to Green Paradox* if it both *raises current fossil fuel supply* and *speeds up exhaustion time* of the fossil fuel.

Note: many “in-between” cases. Then emphasizes *current fossil fuel supply*. 
Policy analysis: solar subsidies under perfect competition
Solar subsidies are subject to Green Paradox under perfect competition

Solar subsidies under perfect competition
- Increase fossil fuel use for all periods;
- Speed up exhaustion of fossil fuels.
- \textit{Strong version} of Green Paradox.

Intuition
- Fossil fuel owners have to exhaust its stock at $T$, when solar becomes competitive.
- Lower solar cost: pushes down fuel price, also solar kicks in earlier.
- Lower $p(t) \rightarrow$ higher extraction.
- Earlier $T$: fossil fuel exhausted earlier.
Solar subsidies: monopoly

Solar subsidies under monopoly
- Reduce current use of fossil fuels (positive).
- Speed up exhaustion of fossil fuels (negative).
Intuition

- The monopolist’s incentive: reduce output in order to raise energy prices.
- But, this incentive is “mitigated” by dynamics: the current vs. future trade-off.
- Depends on relative elasticities of residual demand facing the monopolist in different periods.
- The monopolist produces more (less) in periods with higher (lower) residual demand elasticities.
- Staving-off period: infinite demand elasticity. Produces more.
- As $c_s$ decreases, the period of infinite residual demand elasticity starts earlier: produce less now to enable more production then.
High cost biofuel subsidies under perfect competition

(a) Impact on prices

(b) Impact on fossil fuel use
High cost biofuel subsidies: effects

Subsidies that reduce the cost of high cost biofuels

- Increase fossil fuel use for early periods (negative);
  1. Intuition: lower biofuel cost pushes down fossil fuel price in all periods.
  2. Thus, more fossil fuel is consumed before high cost biofuel kicks in.
- Delays exhaustion of fossil fuels (positive).
  1. High cost biofuel becomes competitive at an earlier time, reducing fossil fuel consumption and delays its exhaustion.

Expanding the capacity of high cost biofuel: similar effects

Message: conclusion about Green Paradox is contradictory if one of the two narrow versions is used (early consumption vs. exhaustion time).
High cost biofuel subsidy: monopoly

- Reduce early use of fossil fuels (positive).
- Speed up exhaustion time of fossil fuels (negative).
Summary

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<tr>
<td>Monopoly</td>
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- Capacity expansion for low cost biofuel: climate friendly.
- Green Paradox: arises only for solar under perfect competition
- Role of capacity constraint (vs solar): exhaustion time effect is opposite to early extraction effect.
- If only concern is with delaying early extraction:
  1. All policies are friendly under monopoly: anticipating future higher elasticity (and thus higher supply), the monopolist reduces current extraction.
  2. Almost all subject to Green Paradox under competition: future renewables suppress current fossil fuel price.
  3. Monopoly is friend of renewable policy
Lessons and next steps

Lessons

1. Difference between subsidies and capacity expansion for biofuels
2. Dynamics important, but be careful about market power: simple dynamic reasoning won’t work.

Calibrated dynamic model

1. NPV of damages (Wang and Zhao, 2015)
2. Heterogeneous fossil fuels: more careful GHG footprints
3. Compare with static predictions

Combine with indirect land use effects: land use decisions are also dynamic!