Innovation, Uncertainty and Instrument Choice for Climate Policy

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Outline

1. Motivation
2. Policy issues
3. The model
4. First-best policy
5. Sensitivity analyses
6. Conclusion
Motivation

- Climate change in a long-term problem
- Energy sector innovation is an integral part of current climate policies
- The existing literature tends to ignore questions of how to combine carbon taxes with innovation subsidies in an intertemporal framework, when competing climate-friendly technologies come into play.
- Uncertainty regarding the cost and availability of alternative non-fossil energy technologies.
- The present paper provides a simple model which describes the issues and illustrates the policy challenges.
Policy Issues

- Public policies affect the prices of carbon based fuels, which in turn affect incentives to undertake research and development (R&D) aimed at bringing alternative fuels to market earlier at a lower cost and/or at a higher capacity.

- Instrument choice involves choosing between technology subsidies or carbon taxes. If there are no market failures apart from the externalities connected to pollution, the cost-minimizing policy is to use carbon taxes alone as they directly target the market imperfection.

- Wigley et al. (1996) examine the optimal timing of CO2 emission abatement if there is a long-term stabilization goal of atmospheric CO2 concentration. Discounted abatement costs are minimized if the bulk of abatement takes place after technology costs are lower.

- Technology development involves knowledge capital which may be public, hence leading to a potential source of market failure.
New Policy Issue: Timing

Timing of climate policy has so far been concentrated to carbon taxes and emissions abatement, but timing is also relevant for a technology subsidy, in particular if we expect new technologies to be developed.

A technology may only be profitable for a certain period of time, and benefits of a technology may be lost with bad timing.

1. How should the optimal technology subsidy evolve over time?

2. How does first-best subsidy and carbon tax policy measures respond to innovation.

3. How does the optimal policy trade-off between the accumulation of physical and knowledge capital stocks.

4. Suboptimal policy may lead to lock-in of the wrong technology, but under which conditions may lock-in be particularly important, and should we avoid subsidizing existing technologies in fear of lock-in?
We examine these issues in the context of a stochastic equilibrium model based on Manne and Barreto (2002).
A Dynamic Model

**Defender** (def), the carbon-based fossil fuel mix of technologies available at low cost; it is neither subject to R&D activities nor resource scarcity within the relevant time horizon;

**Challenger** (chl), the carbon-free challenger technology currently available but not operated in the baseline because it is more costly than the conventional Defender; R&D activities may allow to increase productivity, i.e. reduce costs of the Challenger.

**Advanced** (adv), an advanced carbon-free technology that might become available during this century; this is lower-cost than Challenger and also subject to productivity changes through R&D; in the baseline – without carbon policy constraints – the Advancer is not operated.
Economic Environment

A single representative agent maximize the present value of utility over an infinite horizon:

$$\max U(C) = \sum_{t=0}^{\infty} \frac{\Delta t}{1-\theta} C_t^{1-\theta}$$

subject to constraints:

1. Output is consumed ($C$), invested ($I$) to used in research ($X$) or employed for capital maintenance ($M$):

$$Y_t = C_t + I_t + \sum_j I_{jt}^E + \sum_j X_{jt} + \sum_j M_{jt}$$

2. Output is produced through a nested, constant-elasticity-of-subsitution production function which combines labor, capital and energy inputs:

$$Y_t = \psi \left[ \theta \left( \sum_j E_{jt} \right)^{\rho} + (1-\theta)(L_t^\alpha K_t^{1-\alpha})^{\rho} \right]^{1/\rho}$$
3. Energy based on technology $j$ is produced through inputs of labor and capital inputs:

$$E_{jt} = \psi_j \left[ \beta_j (K_{jt}^E)^\rho + (1 - \beta_j) (\lambda_{jt}L_{jt}^E)^\rho \right]^{1/\rho}$$

4. Capital accumulation in aggregate production based on investment and depreciation:

$$K_{t+1} = K_t (1 - \delta) + I_t$$

5. Capital accumulation in energy sector based on (net) investment and (endogenous) depreciation:

$$K_{jt+1}^E = K_{jt}^E (1 - \delta_{jt}) + \lambda_{jt}J_{jt}^E$$

in which $\lambda_{jt}$ is an index of energy technology $j$ productivity in time period $t$ which affects both labor and investment (embodied technical change).

6. Energy sector productivity is a function of accumulated R&D:

$$\lambda_{jt} = \frac{1 + \ell_j}{1 + \ell_j (\frac{Z_{jt}}{Z_j})^{-\gamma}}$$
where accumulated R&D depends on previous net investments:

\[ Z_{jt+1} = Z_{jt} + \sum_{\tau<t} \Omega_{jt-\tau} RD_{j,\tau} \]

7. Labor supply

\[ L_t + \sum_j L_{jt} = \bar{L}_t \]

8. Depreciation rates for energy capital are an isoelastic function of the level of investment:

\[ \delta^E_{jt} = \psi \left( \frac{K^E_{jt}}{M^E_{jt}} \right)^\epsilon \]

9. Net and gross investment in the energy sector are related through Uzawa’s quadratic adjustment cost model:

\[ I^E_{jt} = J^E_{jt} \left( 1 + \phi \frac{J_{jt}}{2K_{jt}} \right) \]
10. The same adjustment cost model applies for knowledge capital:

\[ RD_{jt} = X_{jt} \left( 1 + \phi^E \frac{X_{jt}}{2Z_{jt}} \right) \]

11. Initial capital stocks (physical and knowledge) are given exogenously:

\[ K_0 = \bar{K}, \quad K^E_{j0} = \bar{K}^E_j, \quad Z_{j0} = \bar{Z}_j \]
Relation to Conventional Bottom-Up Models

In all of Manne’s models, going back to ETA, the transition to new technologies is governed by \textit{expansion} and \textit{contraction} constraints. These inequalities serve the role of technology-specific capital stocks, e.g.

\[
\frac{E_{jt}}{1 + \delta} \leq E_{jt+1} \leq E_{jt}(1 + \epsilon) + \beta
\]

A problem with the linear programming formulation is that expansion and contraction rates are insensitive to changes in relative prices.

Our R&D model is based on explicit physical and knowledge capital stocks, through which rates of entry and exit for energy technologies are endogenous and price-responsive.
Climate Policy Constraint

Emissions are associated only with energy production by \( \text{def} \). Aggregate emissions over an 80 year horizon are subject to a fixed upper bound:

\[
\sum_{t} E_{\text{def},t} \leq \bar{G}
\]
Stochastic Structure

Recourse places a central role in our model. Decisions taken in early years (2006 to 2030) hedge against uncertain future outcome. Three policy instruments: research and development, capital investment and carbon taxes. Investments undertaken in early years hedge against uncertainty about the availability of advanced technology in later years.

State variables in our model include both $K_{jt}^E$ and $Z_{jt}$.

The date at which advanced technology becomes available is the source of uncertainty. Early period investment decisions hedge against uncertainties, taking into account opportunities for adaptation in subsequent periods.
Stochastic Program

$$\text{max } E(U(\tilde{C}))$$

s.t.

State-contingent market constraints:

$$\tilde{Y}_{st} = \tilde{C}_{st} + \tilde{I}_{st} + \sum_j \tilde{I}_{jst}^E + \sum_j \tilde{X}_{jst} + \sum_j \tilde{M}_{jst}$$

etc.
Stochastic Structure

2030
2035
2040
2045
2050
never
Model Solution

- The economic model (with *exogenous* productivity effects) is solved as a complementarity problem using GAMS/MPSGE in annual time steps over a 85 year horizon.

- Stochastic elements of the model are introduced through new tools for stochastic programming in a complementarity format (Meeraus and Rutherford, 2005).
The R&D model is solved as a nonlinear program over a 200 year horizon:

$$\max \sum_{t=0}^{200} \lambda_{jt} V_{jt} - p_t X_{jt} \left( 1 + \phi \frac{X_{jt}}{2Z_{jt}} \right)$$

subject to:

$$\lambda_{jt} = \frac{1 + \ell_j}{1 + \ell_j \left( \frac{Z_{jt}}{\bar{Z}_j} \right)^{-\gamma}}$$

$$Z_{jt+1} = Z_{jt} + \sum_{\tau < t} \Omega_{jt-\tau} RD_{j,\tau}$$

$$Z_{j0} = \bar{Z}_j$$
Technology Parameters

Parameter values are assumed for illustration.

Baseline growth rate for the economy is 2% per year, the baseline energy value share is 5%, and the net interest rate 5%. The depreciation rate is 7% in macro production and 5% in the energy sector.

<table>
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<th>Parameter</th>
<th>def</th>
<th>chl</th>
<th>adv</th>
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<td>Long-Run Cost</td>
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<tr>
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<tr>
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<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Availability</td>
<td>current</td>
<td>current</td>
<td>2030 or later</td>
</tr>
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Imposition of a carbon constraint limits output from DEF to 25% of baseline emissions over the model horizon (2006 to 2090).

This is an unanticipated constraint which leads to a rapid increase in CHL output and compensating decrease in DEF emissions. During the period of 20 years prior to the possible market entrance of ADF, emissions from DEF rise.
CHL is developed response to the carbon emissions constraint. Output declines during the two decades prior to the possible introduction of ADV. Output subsequently rises over time to anticipate the potential failure of a substantive innovation in ADV.
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Growth Rate in CHL Output

Growth of output reflects two factors: growth of the capital stock and improvement in factor productivity. The existence of two capital stocks (physical and knowledge capital) results in a wide variation in growth rates over the model horizon.

Note that output growth responds to “bad news” in each of the resolution points (2030, 2035, 2040, 2045, and 2050).

Knowledge capital does not depreciate, so productivity improvements through R&D occur early in each phase, although there is some attenuation as a result of adjustment costs.
ADV output growth only occurs after discovery. The earlier the discovery, the lower growth response is required. As time goes by, the carbon constraints becomes more tightly binding, and there is a need for more rapid expansion of ADV.
CHL Factor Productivity

This diagram illustrates the consequences of R&D in the CHL sector. A crash program undertaken in the first few years provides a rapid increase in productivity. Subsequent improvements in TFP only result at a later date when it is discovered that ADV is never going to be developed.
Research expenditures for CHL are punctuated. The first research program is undertaken at the outset, as soon as the carbon constraint is discovered.

Subsequent R&D program responds to news about the availability of ADV.

Later research is costly due to diminishing marginal productivity of R&D.
Productivity growth responds immediately following discovery, as would be expected.
As expected, the later ADV is discovered, the greater the need for an intense R&D program.
Future Value Carbon Tax

Given an intertemporal carbon budget, future value carbon taxes increase in inverse proportion to present value prices. This diagram illustrates how the optimal carbon tax rate responds to bad news concerning the availability of ADV energy.
Sensitivity Analyses

1. Sensitivity analysis wrt carbon abatement target (75% versus 50%)
   - CHL productivity development
   - DEF output
   - CHL output

2. Coefficient of relative risk aversion (4 versus 1)
   - CHL output

3. Probability of ADV (0.5 versus 0.8)
   - Carbon tax rate

4. Geometric growth model
   - CHL output

5. Stochastic structure (2020-2040 versus 2030-2050)
   - CHL output
Factor Productivity in CHL

Sensitivity analysis with respect to abatement target.

This figure compares TFP development under an less tightly constrained carbon target. (50% abatement, as compared with 75%)
Defender Output

Sensitivity analysis with respect to abatement target.

When the carbon abatement target is less ambitious, defender output remains at close to business as usual levels.
CHL Output

Sensitivity analysis with respect to abatement target.
CHL Output

Sensitivity analysis with respect to the coefficient of relative risk aversion.
Present-Value Carbon Tax Rate

Sensitivity analysis with respect to the subjective probability of innovation in ADV technology.
Comparison of R&D model with a geometric growth model.
CHL Output

Sensitivity analysis with respect to the resolution of uncertainty.
Summary of Contribution

1. Consistent model which examines the timing of climate policy instruments.

2. Stochastic programming in a complementarity format provides a convenient means of portraying uncertainty in the future development of energy technology.

3. Clean structural model provides a starting point for evaluating second best policy measures and market failures related to the incentives for private sector innovation.
**Future Work** (for this and subsequent papers)

1. Estimation of R&D impacts on technical change.

2. Estimation of adjustment costs for individual energy technologies.

3. Representation of incentives for private R&D.

4. Calibration to an integrated assessment model with climate dynamics and long-term stabilization targets.

5. Representation of individual technology options for transportation and electricity sectors.