How can technology-advancement policies be integrated with emissions-pricing policies?

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In order to meet climate change mitigation targets, significant changes in technological portfolio needed

Low or zero carbon technologies currently have limited range of applications, e.g.:
- Energy: wind, solar, nuclear, CCS
- Transport: biofuels, hydrogen

Significant investment would therefore be needed, particularly in Research and Development of carbon free energy technologies, yet investment in energy R&D technology have declined dramatically since the peak of the early 80s
Historic Energy R&D Expenditure

Million USD

- Conservation
- Nuclear Fusion
- Renewable Energy
- Nuclear Fission
- Other Tech./Research
- Power & Storage Tech.
Research questions

- How can technological innovation be stimulated?
- What is the role or technological innovation in reducing stabilization costs?
- Would a policy to further stimulate technological innovation be granted?
- Could technological innovation policies alone stabilize GHG concentrations?

Effects of carbon price signals, R&D subsidies.
Existing and new technologies, spillovers
A Global International R&D Fund
Technological innovation as stand alone policy
WITCH
World Induced Technical Change Hybrid Model

http://www.feem-web.it/witch/
Hybrid I.A.M.:
- **Economy**: Top-down optimal growth (inter-temporal)
- **Energy**: Energy sector detail (technology scenarios)
- **Climate**: Damage feedback (global variable)

**The WITCH Model**

Economical Activity

Energy Use

Climate

- Temperature
- Emissions

A tool to perform normative, forward looking, strategic analysis
Focus on Endogenous Technical Change

- **Learning by Doing** (LbD) affects the electricity investment costs through decreasing learning curves.

- **Learning by Researching** (LbR) affects:
  - energy efficiency
  - The price of advanced biofuels
  - The cost of investing in a “backstop” carbon free electricity generation technology

- **Technology Spillovers** affects both learning by doing (through world installed capacity) and learning by researching (through country specific absorption capacity)
R&D improving Energy Efficiency in WITCH

The cumulative installed world capacity is used as a proxy for the accrual of knowledge that affects the investment cost of a given technology

\[
SC(t + 1) = A \cdot \sum_n K(n, t)^{-\log_2 PR}
\]

(1)

The stock of energy R&D combines with energy \( EN \) to supply energy services \( ES \) to the final good sector (CES function)

\[
ES(n, t) = \left[ \alpha_H(n)HE(n, t)^{\rho} + \alpha_{EN}(n)EN(n, t)^{\rho} \right]^{1/\rho}
\]

(2)

The stock of knowledge is determined by R&D investment in each region, through an innovation possibility frontier with diminishing returns to investment:

\[
HE(n, t + 1) = aI_{R&D}(n, t)^b HE(n, t)^c + HE(n, t)(1 - \delta_{R&D})
\]

(3)

Investment in energy R&D crowds out other forms of R&D.
Possibility of developing new, breakthrough technologies in both electricity (EL) and non-electricity (NEL) sectors.

Investment costs can be brought down through a 2-factor learning curve, i.e., with investments in R&D (learning by searching) and installed capacity (learning by doing):

\[
\frac{P_{tec,T}}{P_{tec,0}} = \left( \frac{R & D_{tec,T-2}}{R & D_{tec,0}} \right)^{-e} \times \left( \frac{CC_{tec,T}}{CC_{tec,0}} \right)^{-d}
\]

(4)

Where \( e \) and \( d \) are the learning by searching and the learning by doing index, defining the speed of learning:

\[
1 - lr = 2^{-d} \quad \text{and} \quad 1 - lrs = 2^{-e}
\]

(5)

Are the learning ratio \( \rightarrow \) rate at which costs decline with doubling of R&D stock and cumulative capacity respectively.
We use historical data and current expenditures and installed capacity for technologies which are currently under research but not yet commercially available.

Initial prices are set equal to roughly 10 times the 2002 of commercial equivalent.

Backstops substitute linearly for nuclear power in the EL sector, and for oil in the NEL sector.

Uptake of backstop is not immediate because of inertia in the system (upper limit set at 5% and 7% in EL and NEL respectively)
Incentives for energy R&D: Carbon Pricing
Set up:

- Assess impact of carbon pricing on induced technical change (ICT). Two (intertemporally optimal) carbon price paths consistent with:
  - 450ppm (550ppm all gases)
  - 550 ppm (650ppm all gases)
Carbon Price under two stabilisation scenarios

Non linearity in abatement cost as a function of concentration target → increasing difference over time
World energy intensity and carbon intensity trajectories

Both energy savings and energy decarbonisations are brought about...
Investment and costs - renewable energy sources

Investment in W&S are multiplied by 2 and 4 respectively with respect to the BAU.

Investment costs decline by 8% and 16% with respect to the BAU through LbD effects.
Investment and costs - clean carbon technologies

Nuclear power production is expanded – pace of the 80s (35% and 80% above BAU in 2050)

CCS plays an important role – annual sequestration rises starting in 2025, reaching up to 6 Gt CO2eq by 2050
Investments in energy efficiency R&D are significantly higher only with a strong carbon price signal:
- expectations about carbon prices;
- other energy technology more responsive to price signals;
- bulk of mitigation in mild scenarios undertaken in developing countries.
The costs of mitigation with and without technical change

Impacts on global costs negligible of induced technical change are negligible. However, for now, technical change affects energy efficiency only.
The costs of mitigation with limited technological options

Impacts on global costs are affected by the availability of technological options: from 3.9% of GWP to over 7% by 2050.
Incentives for energy R&D: breakthrough technologies
Breakthrough technologies can only become available with substantial investments in R&D: energy R&D expenditures increase to about 0.12% of GDP, vs. 0.08% in the BAU.
The price follows an inverted S curve: R&D expenditures bring costs down rapidly in early stages.

After 2030, price declines are brought about through LbD.
Energy technology mix in the EL sector

The new EL technology substitutes nuclear energy...

Both technologies become quickly important…
Energy technology mix in the NEL sector

...whereas the energy saving constraint in NEL is relaxed
Investments in other low carbon technologies

The new technology in EL crowds out investments in W&S, once it becomes competitive.

On the other hand, CCS and the backstop are complementary → constraints on nuclear and NEL backstop.
Mitigation costs with the backstop technologies

The price of carbon is much lower with the possibility of breakthrough technologies.

And therefore the costs of stabilisation are much lower, especially in the long term.
Mitigation costs with the backstop technologies

Interestingly, it is the availability of the backstop in the NEL sector that helps to bring down global costs of meeting the stabilisation target.
Global R&D Policies and stabilisation costs in the presence of international spillovers: international R&D fund
An international R&D fund

• Policy set up:
  • 550 stabilization scenario
  • International Fund to finance technology development
  • Size of the Fund matching R&D investments of the 80s, starting at 0.08% of world GDP.
  • Each region contributes a share of GDP to the fund, which is reallocated on a per capita basis adding to own energy efficiency R&D efforts.
• When the Fund subsidises investment in energy efficiency R&D, it has a limited impact on costs of meeting the mitigation target: while the knowledge externality is internalised, the carbon price signal alone has significant impacts on energy services, so the additional R&D in energy efficiency has a low marginal effect.

• The Fund has more impact when used to help “decarbonise” the economy
  • Subsidises R&D in the backstops
  • Subsidies to deployment of existing low carbon technologies
The impacts on mitigation costs are higher when the International Fund is used to finance the backstop technologies, but the magnitude is not large.
Subsidising deployment of existing low carbon technologies

The energy mix is significantly affected. W&S become significantly more important by 2050...

...while CCS is important in the earlier stages, whereas in the long term it is limited by the constraints on storage sites.
Mitigation costs with a global fund to finance deployment of existing low carbon technologies

GDP costs initially increase for the contribution to the global fund. In the long term the costs decrease, but marginally.
R&D or deployment subsidies as stand alone policies
In the absence of a carbon price signal, the subsidies to backstop R&D stabilise emissions by mid-century. The effect on concentration is negligible because of inertia in the system.

Hence, limited environmental effectiveness, but increase in GWP → internalisation of knowledge externality.
Global technology deployment subsidies as stand alone policy

...in the absence of a carbon price signal, subsidising deployment of existing technologies has a quicker impact on emissions...

...but the effect gradually fades out, and atmospheric concentration continue to increase.
Summarising the main results…
Carbon price signals

• Technological change key role to play in supporting the transition to low carbon economies, hence reducing the costs of meeting a stabilisation target.

• **Carbon price signals:**
  – an important stimulus to technological innovation, both in inducing higher investments in R&D and more deployment of existing low carbon technologies such as W&S and CCS
  – Credibility of future climate change commitments and expectations about future carbon prices matter for today’s investment decisions.
The role of existing technologies

• **Induced technological change with existing technologies**
  – Without the possibility of breakthrough technologies, however, higher R&D investments have limited impacts on the costs of stabilisation.
    • Decreasing marginal returns to investment in R&D and LbD to deployment
    • Alternatives in energy sector: expansion of nuclear and IGGC+CCS
  – Indeed, when these low carbon alternatives are limited, overall mitigations costs increase significantly
The role of breakthrough technologies

• **Induced technological change and new technologies**
  – With the possibility of breakthrough technologies in EL and NEL, the costs of stabilisation decrease substantially – by half in 2050.
  – Alternatives in NEL are more important, as in EL low carbon technologies already exist.
  – Importantly, even with the possibility of breakthrough technologies, a strong price signal is needed to induce technological innovation.
Policies to stimulate technological innovation

- **A global fund to induce technical innovation…**
  - Can further lower the costs of mitigation, in particular when the subsidies are used for “decarbonising” the economy
  - However, R&D or deployment subsidies alone are not a policy option to tackle climate change: while emissions can somewhat be reduced, atmospheric concentrations are not stabilised.
Sensitivity analysis: Learning by Doing
Effects of varying LbD ratio in W&S

...uptake of renewable energy, in a stabilisation scenario, clearly depends on the LbD assumed...

...but the effect on global costs is negligible
Sensitivity analysis: returns on R&D
Impacts of changing effectiveness in R&D

World investment in energy efficiency improving R&D

- Low R&D productivity
- Central R&D productivity assumption
- High R&D productivity

Investments in energy efficiency R&D increase with improved effectiveness...

…but the effect on global costs remains negligible
Sensitivity analysis: specification of the backstop technologies
Learning ratios for the backstop technologies

Learning rate assumptions have a significant impact on the penetration of the backstop technologies...

...and therefore also on the global costs of meeting the stabilisation target, though the effects are not symmetric.
The effects are similar as varying learning rates in research and deployment…

…albeit the effects on the global costs of meeting the stabilisation target albeit less asymmetric
Specification of Technology Spillovers in WITCH
• New technologies are created and developed in a handful of countries: in 1995 G7 countries accounted for 84% of world spending on R&D; at the same time their share of GWP was 64%

• The pattern of worldwide technical change is determined in large part by international technology diffusion

• Major channels are international trade, foreign direct investment and disembodied knowledge flows (patents, blueprints, research in labs and think tanks)

• We focus here on disembodied, energy related, knowledge spillovers.
Energy R&D Flows and Stabilization Policies

*Basic question:* Does more technology diffusion lead to more technological innovation and lower stabilization costs?

- The idea is very attractive and has been put forward by many authors (Barrett, 1994, 2002; Carraro and Siniscalco, 1997; Grubb, Hope and Fouquet, 2002; Philibert, 2004)

- However, more spillovers may increase the incentives to free-ride on knowledge production thus reducing R&D investments worldwide. In addition, more technology diffusion may induce higher growth and therefore more GHG emissions (Buonanno, Carraro and Galeotti, 2003).
The Model

WITCH with International Knowledge Spillovers
Main Features

- WITCH: a “TOP DOWN” optimization framework, with a energy sector description (“BOTTOM UP”) as a downward expansion of the energy input

  - Ramsey-type neo-classical optimal growth (dynamic, perfect foresight)
  - Detailed energy input specification
  - Hard-link (stand-alone optimization) hybrid
  - World: 12 regions, interacting strategically (open-loop dynamic game)
  - Endogenous Technical Change in energy sector
  - Climate module feedback
Endogenous Technical Change

- **Learning by Doing (LbD)** affects the electricity investment costs through decreasing learning curves.

- **Learning by Researching (LbR)** affects:
  - Energy efficiency
  - The price of advanced biofuels
  - The cost of investing in a “backstop” carbon free electricity generation technology

- **Technology Spillovers** affects both learning by doing (through world installed capacity) and learning by researching (through country specific absorption capacity).
The stock of energy R&D $HE$ combines with energy $EN$ to supply energy services $ES$ to the final good sector

$$ES(n,t) \equiv HE(n,t) + EN(n,t)$$  \hspace{1cm} (1)$$

The R&D sector exhibits intertemporal spillovers and the production of new "ideas" follows an innovation possibility frontier (Kennedy, 1964). Diminishing returns to scale, i.e. $(b + c) < 1$ (Popp, 2004):

$$Z(n,t) \equiv a R&D(n,t)^b HE(n,t)^c$$  \hspace{1cm} (2)$$

The flow of new ideas add to the stock (depreciated by obsolescence) and generates the total amount of knowledge available to country $n$ at time $t$:

$$HE(n,t) \equiv HE(n,t)(1 - R&D) + Z(n,t)$$  \hspace{1cm} (3)$$
International R&D Spillovers

A three-steps approach guided our modelling choices:

1. Define size and characteristics of the international knowledge pool
   - Are knowledge stocks cumulated in different countries heterogeneous or homogeneous?

2. Describe the process of knowledge absorption
   - Are spillovers a "manna from heaven" or domestic effort/technology is needed to absorb foreign knowledge?

3. Describe how spillovers combine with the domestic knowledge production sector
   - Does foreign knowledge complement or crowd out domestic investments?
   - Is productivity of domestic investments affected?
Two views of the International Knowledge Pool

1. Technological development is seen as a process in which all countries move upwards on the same knowledge ladder

   - Laggards harvest substantial gains

   - Innovators receive scarce or no benefit from exposure to international knowledge

   - Gerschenkron (1962): *Economic Backwardness in Historical Perspective*

   - Acemoglu, Aghion and Zilibotti (2006)
2. Countries move along independent technological patterns, thus any technological flow increases domestic knowledge stock

- Basic idea is path dependence (Rosenberg, 1994): technological development of countries follows patterns influenced by history (e.g. regulation)

- For energy technologies this seems to be a good description of technological progress: wind industry, car engines

- Also leading innovators receive benefits from international knowledge flows
• Both these representations capture some important features of technology diffusion. In this paper, we assume that:

• **Low Income** (LI) countries absorb knowledge from the frontier, i.e. the *Gerschenkron effect* prevails.

• In **High Income** (HI) countries capital stocks are heterogeneous and technologies may be different. The *Rosenberg effect* prevails.

• We combine the two different representations in one single formulation by assuming that the *technological frontier* is set by the whole group of High Income countries.

• The *technological frontier* is measured by the sum of the stocks of R&D capital detained by High Income countries

\[
KP(n,t) = \sum_{n \in HI} HE(n,t) - HE(n)\]  

(4)
2. The Process of Knowledge Absorption

• Only a fraction \( ?(n,t) \) of the available total pool of knowledge is absorbed by each country.

• The process of learning, far from being free, is costly and most of this cost is borne in the receiving country (Cohen and Levinthal, 1989; Keller, 2004; Kneller, 2005).

• The absorption capacity is a function of the distance between the R&D capital cumulated in the region and the technological frontier.

\[
? (n,t) \sim \frac{HE \cdot n,t}{n \cdot HE \cdot n,t} \quad (5)
\]
The overall inflow of foreign knowledge, \( \text{SPILL}(n,t) \), is thus:

\[
\text{SPILL}(n,t) = \gamma(n,t) \cdot \text{KP}(n,t)
\]

\[
= \frac{\text{HE}(n,t)}{\sum_{n \in \text{HI}} \text{HE}(n,t)} \left[ \sum_{n \in \text{HI}} \text{HE}(n,t) - \text{HE}(n,t) \right]
\]

\( (6) \)

- The farther one country lies from the technological frontier:
  - the bigger is the knowledge pool that is available for absorption, the smaller is its capacity to absorb
  - inverted U curve

- The low absorptive capacity of Low Income countries realistically reduces the potentially very large inflow of knowledge from the technological frontier

- High Income countries may see their absorptive capacity to decline over time if they miss to innovate at the same pace of their technologically advanced partners
3. The Use of Spillovers

• The third and final step consists in defining how countries use the R&D spillovers in the process of domestic knowledge generation.

• Spillovers enter the domestic R&D sector as an input in the innovation possibility frontier; an analogous aggregation is found in Acemoglu (2002):

$$Z_n, t = a_n H_{R&D}(n, t)^b HE(n, t)^c SPILL n, t$$  \(8\)

• Easy to control for the elasticity of domestic knowledge to international knowledge spillovers.
Do free-riding incentives prevail?

- By giving R&D investments a role in the process of knowledge absorption and by letting international R&D spillovers to augment the productivity of domestic investments we have introduced forces that work against the free_riding incentives.

- This is in accordance with the most advanced literature on knowledge spillovers:
  - Cohen and Levinthal (1989): when domestic R&D increases the absorption capacity and some general conditions holds, the incentive to invest more in R&D offsets the disincentive represented by free-riding and world investment in R&D eventually increases.
  - Does this hold true in the world described by the WITCH model?
Calibration
Choice of Elasticity to Spillovers

\[ Z \frac{\partial h}{\partial t} = a h^b R&D(n,t)^c HE(n,t)^d SPILL h, t \]  

(8)

- We set the parameter \( d \) equal to 0.15, i.e. an increase of 1% of international spillovers increases domestic knowledge by 0.15%.

- To our knowledge, there is no empirical evidence that may suggest a value for the parameter \( d \).

- We set \( d \) at a value slightly lower than the elasticity of knowledge production to domestic investments (0.18), and about one third of the elasticity with respect to the R&D capital stock (which was equal to 0.53 in the model without spillovers).
  
  - Priority to the domestic investment in generating new discoveries
  - Intertemporal knowledge spillovers are stronger than the international ones

- **Sensitivity analysis** to check the calibrated parameters.
Stabilization of CO$_2$ emissions
• Target: CO$_2$ concentrations stabilised at **450ppmv** by the end of the 21st century.

• Two cases: Without and with international spillovers

• Policy instrument: a world carbon market that equalizes marginal abatement costs worldwide. Emissions permits allocated according to the "Equal per Capita" scheme.
• World investments in R&D are always lower when spillovers are accounted for.

• High Income countries reduce investments the most.

• For Low Income countries we record only a mild reduction, increasing and then decreasing over the century.

• In LI countries spillovers increase at a faster rate than in HI ones as they move along the bell-shaped curve that governs knowledge inflows.

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Table 1. Variation of R&D Investments when Spillovers are Modelled.
R&D Energy Spillovers and Stabilization Costs

• International spillovers substitute for domestic investments and the savings from less investments are spread across the economy

• Gains in terms of stabilization costs are negligible

• As an example, over the whole century the USA save 50 USD Billions over a cumulated GDP of more than 350 Trillions in our stabilization scenario, i.e. a modest 0.06%

• The stock of R&D capital only slightly changes. Hence:
  – no adjustments in the investment in all other technologies
  – price of emissions permits does not change when spillovers are introduced
Policy Analysis:
Building Absorption Capacity in Low Income Countries
Transfers to Enhance Absorption Capacity

• Stabilization of atmospheric GHG concentrations at 450ppmv.
• Two policy instruments: emission permits and transfers to foster technology diffusion through enhanced absorption capacity
• Emission permits distributed according to the “Sovereignty rule”
• HI countries use a fraction of the revenues from emission permits sales to enhance absorption capacity in LI regions:

\[ Z(n,t) \cdot a_I R&D(n,t)^b \ HE(n,t)^c \ HE(n,t)^d \ ABS(n,t)^e \ HE(n,t)^f \ ABS(n,t)^g \ HE(n,t)^h \ ABS(n,t)^i \ AID(n,t)^j \]  

- **ABS** is the enhanced absorption capacity achieved through transfers from HI countries:

\[ ABS(n,t + 1) ? ABS(n,t)^k ? ? ? AID(n,t)^l \]
### Stabilization Costs

- Lower stabilization costs in LI countries
- HI are worse off but World as a whole is better off
- Simple transfer policy (compensation for LI countries) is less efficient

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Table 6. Stabilization Costs as Share of GDP.
R&D investments in LI increase thanks to the productivity enhancing effect of greater absorption capacity.

Same result as in Cohen and Levinthal (1989).

In HI countries slight decline of R&D due to lower available revenue.

### Table 8. Cumulative Investment in R&D, 2002-2102.

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Convergence Among High Income

- Among High Income countries the greatest reductions are recorded in the USA, OLDEUROPE and CAJANZ

- KOSAU and NEWEUROPE have a lower reduction of investments than the top three countries

- The share of investments at the frontier for KOSAU and NEWEUROPE, i.e. the share of all High Income countries’ investments, increases of about 4% and 2%, respectively, in the first decades of the century

- Spillovers increases converge among countries at the frontier

<table>
<thead>
<tr>
<th></th>
<th>2022</th>
<th>2042</th>
<th>2062</th>
<th>2082</th>
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Table 2. Variation of Share of High Income Countries Investments.
Convergence Among Low and High Income

- As a group, Low Income countries increase their share of world investments of 2% between 2002 and 2032 and remain rather stable across the century.

- High Income countries, as a group lose grounds in favour of Low Income countries in the first decades of the century.

- Convergence issues from multiple perspectives.

- Spillovers thus reinforce the already strong convergence in our stabilization scenario without spillovers.

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<th>2062</th>
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Table 3. Variation of Share of World Investments in Energy R&D.