FONDAZIONE ENI ENRICO MATTEI

NOTA DI LAVORO

33.2010

The Role of International Carbon Offsets in a Second-best Climate Policy: A Numerical Evaluation

By **Enrica De Cian,** Fondazione Eni Enrico Mattei and University of Venice, Italy

Massimo Tavoni, Princeton Environmental Institute, USA Fondazione Eni Enrico Mattei, and Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC), Italy

SUSTAINABLE DEVELOPMENT Series
Editor: Carlo Carraro

The Role of International Carbon Offsets in a Second-best Climate Policy: A Numerical Evaluation

By Enrica De Cian, Fondazione Eni Enrico Mattei and University of Venice, Italy
Massimo Tavoni, Princeton Environmental Institute, USA, Fondazione Eni Enrico Mattei, and Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC), Italy

Summary

International carbon offsets have been promoted since the Kyoto Protocol and an increasing number of countries have implemented or proposed cap-and-trade schemes with international trading, even though with quantitative or qualitative restrictions. Those limits reflect the trade-off between economic efficiency, distributional issues, and the need for additionality of foreign mitigation measures. Ceilings are also justified on the ground that international offsets undermine the capability of climate policy to induce and diffuse technological change. This paper addresses these issues in a second-best setting that explicitly considers the interplay between multiple externalities. We evaluate numerically how limits to the size, the timing, and the participation in an international carbon market affect the macroeconomic costs of climate policy, international financial transfers, and the incentive to carry out innovation. Results indicate that when constraints on international offsets are moderate, such as limiting their use to at most 15% of regional abatement, efficiency losses are small because they are partly compensated by more technological change and energy market effects, although specific regional patterns are identified. Regarding financial outflows from OECD countries, already a 15% ceiling would limit financial transfers significantly. Provisions of this kind are in line with some of the most recent policy proposals in OECD countries.

Keywords: Energy-economy Modelling, Climate Policy, Technology Spillovers

JEL Classification: Q54, Q55, Q43, H23

This paper is part of the research carried out by the Sustainable Development Programme of Fondazione Enrico Mattei. Financial contribution from the PLANETS project funded by the European Commission under the 7th framework programme is gratefully acknowledged. The usual disclaimer applies.

Address for correspondence:

Enrica De Cian
Fondazione Eni Enrico Mattei
Campo Santa Maria Formosa
Castello 5252
30122 Venice
Italy
E-mail: enrica.decian@feem.it

The role of international carbon offsets in a second-best climate policy: A numerical evaluation.

Enrica De Cian[1] and Massimo Tavoni[2]

Abstract

International carbon offsets have been promoted since the Kyoto Protocol and an increasing number of countries have implemented or proposed cap-and-trade schemes with international trading, even though with quantitative or qualitative restrictions. Those limits reflect the trade-off between economic efficiency, distributional issues, and the need for additionality of foreign mitigation measures. Ceilings are also justified on the ground that international offsets undermine the capability of climate policy to induce and diffuse technological change.

This paper addresses these issues in a second-best setting that explicitly considers the interplay between multiple externalities. We evaluate numerically how limits to the size, the timing, and the participation to an international carbon market affect the macroeconomic costs of climate policy, international financial transfers, and the incentive to carry out innovation.

Results indicate that when constraints on international offsets are moderate, such as limiting their use to at most 15% of regional abatement, efficiency losses are small because they are partly compensated by more technological change and energy market effects, although specific regional patterns are identified. Regarding financial outflows from OECD countries, already a 15% ceiling would limit financial transfers significantly. Provisions of this kind are in line with some of the most recent policy proposals in OECD countries.

Keywords: Energy-economy modelling, Climate policy, Technology spillovers
JEL Classification: Q54, Q55, Q43 and H23

This paper is part of the research carried out by the Sustainable Development Programme of Fondazione Enrico Mattei. Financial contribution from the PLANETS project funded by the European Commission under the 7th framework programme is gratefully acknowledged. The usual disclaimer applies.

Address for correspondence:
Enrica De Cian
Fondazione Eni Enrico Mattei
Campo Santa Maria Formosa, Castello 5252, 30122
Venice, Italy
e-mail: enrica.decian@feem.it

[1] Fondazione EnI Enrico Mattei (FEEM) and University of Venice.
[2] Princeton Environmental Institute, FEEM, and Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC).

1. Introduction

Since the Kyoto Protocol Clean Development Mechanism (CDM), international offsets have been considered an important ingredient of any efficient solution to climate change. International emission trading has the potential to reduce compliance costs because it makes it possible to exploit low cost mitigation options wherever they are located. Following this argument, numerous regional and sub-regional carbon market initiatives, either regulated or on a voluntary base, have emerged especially in developed countries[3].

International offsets have also been a controversial issue. It is an important cost-containment mechanism, but if not well-designed it may undermine environmental effectiveness and technological change. In 2000, a lack of agreement on the implementation procedures of the Kyoto mechanisms led to the failure of negotiations at Hague. In 2004, the EU linking directive established the possibility to use Kyoto credits in the EU-ETS, without any limit. During the second Phase of emission trading, the EU decided to limit the quantity and the quality of offsets to avoid the price collapse faced during the first Phase.

Most of the existing or proposed cap-and-trade schemes include ceilings on international offsets. For example, the Waxman-Markey Bill allows approximately 1 Billion tons of CO2 annually for international offsets (only half of this figure is considered in the currently discussed Senate bill by Kerry and Boxer). The European Union has proposed a cap between 1.4 and 1.6 Billion tons for the period between 2008 and 2020, an amount that could be increased in the case of more ambitious reduction. The Canadian emission trading scheme which should be launched in 2010 also contains a 10% limitation to the purchase of international offsets from CDM. Japan's newly elected Prime Minister has increased the target on emission reduction from 8 to 25% by 2020 and he has proposed to cover up to 60% of its emission target through foreign carbon credits[4].

A well-designed, global cap-trade-system has the potential to create the right incentives to engage developing countries (Wara and Victor 2008, Frankel 2008). However, if most of the reduction burden were allocated to industrialised countries, then an unconstrained scheme would create a system of transfers from developed to developing countries. These flows might be substantial and arguably controversial. For example, Jacoby et. al (2008) found that the size of north-south side-

[3] For a review of cap and trade schemes around the world see Capoor and Ambrosi (2009).
[4] http://www.mofa.go.jp/policy/un/assembly2009/pm0922.html; http://www.pointcarbon.com/news/1.1272010

payments would already reach US$ 400 Billion in 2020. This is four times the current spending on Official Development Assistance[5]. Furthermore, a well-functioning carbon market requires a solid infrastructure that guarantees the integrity of the transactions and provides market participants with reliable information. It also requires high quality monitoring, reporting, and verification. The experience with CDM, the largest existing international carbon market, has already revealed major problems concerning credit verification and quality certification of the projects involved (Wara and Victor 2008). As long as these issues are not solved, institutional or administrative issues are likely to delay the establishment of a global market.

An additional line of reasoning is often promoted to discourage heavy reliance on international carbon offsets. When a polluting country faces the choice of whether innovating or purchase carbon credits, the cheapest option will be selected (Driesen 2003). If permits are cheaper than investment costs in mitigation options at home, emission trading will create an incentive to shift abatement abroad, reducing total compliance costs, but also lowering the incentive to carry out innovation. This is a known argument (see for example Hourcade et al. 1999), which has been proposed again recently within the EU-ETS. Since the price collapse in 2006, the EU Commissions has favoured quantitative and qualitative restrictions on international offsets (de Sépibus 2008).

As discussed in Karp and Zhao (2009), if limits to purchase credits are not large, economic losses might be modest and therefore it may be worthy to use them. These limits could avoid huge transfers to developing countries, make the agreement more appealing for industrialised countries, and stimulate innovation. The argument in favour of ceilings might be reinforced in a second-best world. Most estimates of the cost-saving effect of unrestricted emission trading schemes hold in a first-best world (e.g. Weyant and Hill 1999, Bohm 1999, Chander et al. 2002, Paltsev et al. 2008, Richels 2007). When the only distortion is global pollution, international emission trading generates efficiency gains. However, the theory of a second-best world (Lipsey and Lancaster 1956) suggests that addressing only one of the various market distortions, will not necessarily improve welfare. Environmental economic literature suggests that multiple policy instruments should be employed, see Jaffe et al. (2003), Jaffe et al. (2005) and Bennear and Stavins (2007). In practice, however, designing several instruments can be complicated, and despite the various forms of regulation used

[5] The amount of money that developed countries should spend for climate change in developing countries has been the leading question of the latest Conference of Parties held in Copenhagen last December. The amount of annual funds agreed upon (US$ 30 Billion from 2010 to 2012 and US$ 100 Billion by 2020) is much less than what developing countries demanded for.

today, a market-based solution aimed at pricing CO_2 is widely regarded as the most probable solution for the case of global warming.

The question of interest here is whether, in the presence of multiple externalities, restricting the use of international carbon offsets is a second-best policy recommendation. Market failures associated with the environmental externality interact with market failures associated with innovation and the diffusion of technologies. Climate policy is targeted at the environmental externality, but it is likely to have second order effects on the technology externality as well. Limiting international emission trading would lead to welfare losses in a first-best world. In a second-best world this might not be the case.

Few studies have addressed this issue. Golombek and Hoel (2006) analysed the welfare implications of trade in carbon permits in a second-best world where technology externalities are not internalised. They found that the second-best optimum is characterised by marginal costs of abatement exceeding the Pigovian tax in all countries. A tighter emission requirement is thus a way of compensating for the lack of technology policy. In a follow-up paper, Golombek and Hoel (2008) found that the price of carbon should differ across heterogeneous countries in the second-best agreement. If the quota are assigned according to the second-best optimum, then there should be no emission trading. Whether emission trading is welfare enhancing or not, is an empirical question.

However, hardly any numerical evaluation of the economic role of international carbon offsets considers the role of technology externalities. Quantitative assessments in a second-best framework have mostly explored the role of pre-existing distortionary taxes. Babiker et al. (2004) and Paltsev et al. (2007) analysed the role of international emission trading in a second-best world, where the carbon price interacts with pre-exiting distortionary taxes. In that setting, terms-of-trade deterioration and tax-interaction effects prevail and emission trading leads to welfare losses in some regions. In the same manner, McKibbin et al. (1999) demonstrated how a country may lose from falling terms of trade after engaging in international emissions trading.

Buonanno et al. (2000) assessed the pros and cons of introducing ceilings to emission trading in a model with endogenous technical change (ETC-RICE). They found little support for quantitative restrictions, which have negative impacts on both efficiency and equity. Although quantitative restrictions foster technological innovation, its long-run positive effects on economic growth are lower than the additional economic costs. Their model does not include international spillovers of knowledge and experience and therefore it underestimates the benefits of technological innovation.

This paper provides a systematic and quantitative assessment of the role of international offsets in climate change policies. Using an integrated assessment model (see Section 2 and the Appendix) that features both environmental and technology externalities, we evaluate the impacts of offsets availability on macroeconomic costs, financial transfers, and innovation.

Results show that in the presence of a climate policy consistent with a 530 ppm-eq stabilisation target, where developed countries initially take on the largest obligations, an unrestricted international carbon market would lead to rapidly growing financial transfers. Limiting access to international offsets makes abatement more costly globally and for the OECD as a whole, but the efficiency losses are small for moderate trading restrictions. Constraining offsets to at most 15% of regional abatement is approximately in line with the current proposals of Boxer and Kerry and with the EU-ETS. This would not affect welfare in the US, though it would result in a loss for Europe. However, financial flows to developing countries would be significantly reduced. Despite the revenue loss on the carbon market, non-OECD regions would be compensated by higher technological spillovers and lower energy prices. A limited access to international offsets spurs more innovation in constrained regions (OECD), which are also the most R&D-intensive countries.
Considering the effects on macroeconomic costs, financial flows, and innovation, our results indicate that a moderate quantitative limit on international offsets might be a second-best policy recommendation.

The remainder of the paper is organised as follows. Section 2 describes the scenario set-up and the model. Section 3 illustrates the macroeconomic implications when international offsets can be used without constraints. Section 4 examines the consequences of restricting the use of permit trading. Section 5 analyses the results for United States and Europe. Section 6 summarises and concludes.

2. Design of the climate scenario and methodology

The choice of the climate scenario is important for the analysis of carbon trading, since the size of the market depends on the overall stringency of the climate objective as well as the regional repartition of the mitigation burden. In this exercise, we consider a climate policy with a long-run stabilisation objective of 530 CO_2-eq ppm (3.5 W/m^2), where most of the initial mitigation effort is on developed regions. A target of this kind is less stringent than what is required to achieve the 2 degrees Celsius objective, but would nonetheless necessitate very significant global mitigation in the next few decades. More stringent commitments in the developed countries match the graduation approach envisaged by the UNFCCC, aimed at accounting for differentiated responsibilities.

Table 1 describes regional commitments to be achieved by 2050. OECD countries subscribe to an allocation requiring a 90% cut of GHGs[6] by 2050 compared to 2005 levels. Non-OECD countries are allowed to increase emissions by 20% which, compared to our baseline projections, implies a reduction of almost 50%. Commitment starting dates have also been differentiated between developed and developing regions, with a 10 year-delay in non-OECD regions. We assume that beyond 2050, all regions will cooperate to reach the long-term stabilisation target and each region will be allocated emission permits proportionally to the emission share in 2050.

Table 1. Emission reduction commitments by 2050

	Starting date of commitment	Emission reduction compared to 2005	Emission reduction compared to BaU
OECD	2015	-90%	-93%
Non-OECD	2025	+20%	-47%
WORLD		-26%	-61%

The chosen scheme shares the main characteristics of other policy architectures recently proposed in the literature (Victor 2007, Bosetti et al. 2008, Bosetti and Frankel 2009, Frankel 2008). It allocates an ambitious reduction to industrialised regions and it delays effort in developing countries. Since international emission trading starts in 2020, developing countries can benefit from their position as net sellers and from the related inflows of financial resources.

In 2020, OECD countries have a target of 18% compared to 2005, and the EU is assumed to comply with the 20% reduction target[7]. Compared to 2005, United States reduces emissions by 14%, Korea, South Africa and Australia by 18%, Canada, Japan and New Zealand by 17%. These reductions are comparable to what policy makers have been proposing recently. In the United States the Waxman-

[6] We only consider the Kyoto gases and do not account for the mitigation option of reduced emissions from deforestation and land use degradation (REDD). Although it is plausible to think that tropical deforestation will play a role in a future international carbon market, concerns with its readiness and reliability led us to exclude it from the mitigation basket.

Markey Bill (the American Clean-Energy and Security Act, or ACES Act 8) acknowledges a 17% reduction by 2020. In Japan the newly elected Prime Minister has proposed a reduction of 25% by 2020, relative to 1990. Similarly, Canada has recommended a reduction of 20% . In Australia, emission reduction ranges between 15% in the presence of a global agreement and 25% under specific conditions[9].

The economic and financial implications of this policy are analysed using the integrated assessment model WITCH[10]. WITCH (Bosetti et al. 2006, Bosetti et al. 2009) is a hybrid energy-economy model with perfect foresight. The WITCH model can characterise second-best equilibria because it considers different sources of market failure: the environmental externality, international knowledge and experience spillovers, and carbon leakage through international energy markets. A full description of how the externalities are represented and solved in the WITCH model can be found in the Appendix.

The model includes a range of technology options that describe the final use of energy and power generation. Electricity can be generated using low carbon options, such as nuclear and hydroelectric power, coal with carbon capture and sequestration (CCS), wind turbines, and photovoltaic panels. We model diffusion processes via experience curves, though only for the innovative technologies. The model also includes Learning-By-Searching in which R&D investments endogenously lead to improvements in energy efficiency and to reduced costs of advanced low carbon technologies.

Both energy innovation and diffusion are activities characterised by international spillovers (Bosetti et. al. 2008a). Each region can benefit from the stock of knowledge developed elsewhere through domestic investments. However, the appropriation of the benefits from knowledge spillovers requires local investments to build up absorptive capacity. A time lag in the spillover of knowledge pool is also assumed. On the contrary, international experience spillovers are free and they are determined by the global deployment of the technology.

Besides technology spillovers, two additional channels of interaction are the international markets of exhaustible resources and the carbon market. International prices of fossil fuels are determined

---

[7] The European Union has proposed reductions up to 30% by 2020, compared to 1990, in the presence of an international agreement. In this paper we assume a 20% reduction by 2020, compared to 1990, because the policy becomes global only after 2020, http://ec.europa.eu/environment/climat/climate_action.htm.
[8] http://www.govtrack.us/congress/bill.xpd?bill=h111-2454
[9] http://www.climatechange.gov.au/
[10] See www.witchmodel.org for model description and related papers.

by total extraction, which in turn depends on regional consumption. When there is a climate policy, countries buy and sell carbon permits until the international carbon market clears, determining a unique global carbon price.

The structure of the model allows us to consider the most salient features of the climate mitigation policy, and to do so in a second-best setting. Although this model is a step-up over standard integrated assessment modelling that normally features only the climate externality, it falls short of thoroughly representing a second-best world. For example, no international trade of capital is assumed and pre-exiting distortionary taxes and subsidies are not accounted for in this exercise. Our model captures market failures related to international spillovers only in the energy sector, as no general purpose R&D is assumed. No learning is considered for known, yet potentially improvable technologies, such as nuclear power and carbon capture and storage (CCS). Thus, this exercise provides an account of only some of the most relevant sources of global interaction.

3. No restrictions on the use of international carbon offsets

We begin by evaluating the implications of the climate stabilisation scenario on economic activity and carbon market when no exogenous constraint is imposed on international permit trading. We refer to this case as the "full offsets hypothesis". Full cooperation is assumed to be supported by a fully-fledged, perfectly functioning, international carbon market, which is operative from 2020 onward.

3.1 Macroeconomic costs

The macroeconomic costs induced by the chosen stabilisation policy are reported in Table 2, in absolute levels and in percentage terms. OECD countries face higher costs as they have signed upon the tightest commitments. Non-OECD countries slightly gain until mid century, mostly due to permit revenues, but lose in the long-term.

Table 2. Global and regional macroeconomic costs of climate stabilisation policy under the "full offsets hypothesis." Consumption losses discounted at 3% discount rate, 2005-2100

Consumption	OECD	Non-OECD	WORLD
US$ Trillion	26.19	1.88	28.07
Percentage of BaU consumption	1.68%	0.18%	1.07%

Losses are gross of climate change damages. Negative numbers indicate gains.

The 1% global figure lies within the range reported in the literature (IPCC 2007), though one should keep in mind that the climate stabilisation objective considered here is not very ambitious compared to the 2 degrees Celsius. The RECIPE model intercomparison analysed the economics of a comparable climate policy and it found that stabilisation costs range between 1.4% and 0.1% of global discounted consumption (Luderer et al. 2009). Low costs are also due to the assumption of immediate participation and full flexibility among greenhouse gases abatement options. Departure from any of these assumptions increases costs substantially. For example, Bosetti et al. (2009) found that limited availability of mitigation technologies would impose an additional penalty of roughly 70% whereas a 20-year delay in global action would increase costs by 160%. The role of delayed participation of developing countries was also emphasised in the recent EMF22 modelling comparison exercise (Clarke et al. 2009).

3.2 The carbon market and financial implications: the "full offsets hypothesis"

Without any restriction, countries rely on the international carbon market, an important element of flexibility that increases efficiency. Table 3 shows the evolution of the carbon market over time. The market size is already significant in 2020, when almost 3 Billion tons of CO2 (equal to roughly half of today's emissions in the US) are exchanged internationally, enough to require the establishment of considerable institutional and monitoring capacity. The initially low carbon price (due to the assumption of global participation and wide basket of GHGs) is such that the market value is contained at the outset, but grows significantly over time, driven by the convex path of the carbon price.

Table 3. International carbon market under the "full offsets hypothesis"

	Mkt size (GtCO2-eq)	GtCO2-eq abated	Internationally traded abatement	Carbon Price (US$/tCO2)	Mkt value (US$ Billion)	Mkt value (% of GWP)
2020	2.8	7	41%	4	11	0.02%
2025	3.0	14	22%	26	76	0.10%
2030	3.3	20	16.%	58	193	0.22%
2050	7.1	46	16%	319	2260	1.74%

The rapid expansion of the carbon market mobilises significant financial resources. In absolute values, the transfers at stake increase from amounts comparable to current Official Development Assistance (ODA) flows already in 2025 (US$ 76 Billion, or 0.1% of Gross World Product) to over US$ 2 Trillion in 2050. As a comparison, today's OECD imports of oil (at a price of 70$/bbl) equate roughly US$ 700 Billion. In terms of regional GDP, outflows from OECD regions increase to US$ 1.7 Trillion in 2050, which is more than 2% of OECD GDP (Table 4).

Table 4. International carbon market under the "full offsets hypothesis". Financial flows as a percentage of regional GDP

	OECD	**Non-OECD**
2020	0.02%	-0.05%
2025	0.14%	-0.29%
2030	0.33%	-0.59%
2050	2.37%	-2.91%

Positive numbers represent outflows, negative numbers represent inflows

It stands that a well functioning international carbon market could provide the means to finance climate change. However, if unrestricted, the amount of transfers required may eventually be too high to be acceptable. Already in 2030, it would be above what Annex I Parties agreed to forego in the Copenhagen Accord, which acknowledges US$ 100 Billion per year starting from 2020.

Therefore, OECD countries face a trade-off. On the one hand, *laissez fair* would maximise cost-effectiveness and contain economic costs. On the other hand, it would entail substantial financial flows, which may undermine the willingness of industrialised countries to commit. If the climate externality were the only distortion in the economy, restrictions to carbon trade would create a wedge in marginal abatement costs across countries, reducing economic efficiency. However, restricting trade might be a second-best policy recommendation. At the same time, a perfectly functioning international carbon market might not be available in 2020 because technical problems such as the lack of institutional capacity, reliable monitoring, and verification systems might delay or fragment the establishment of a global market.

The next section tackles both issues and it considers a departure from the "full offsets hypothesis" along three directions:

- "*When*": the establishment of an international carbon market is delayed to a future date between 2030 and 2045
- "*How much*": until 2045, only a fraction of abatement, ranging from 20% to 10% of regional abatement, can be met through the international carbon market
- "*Where*": only a subset of regions joins from the outset (2020) of the international carbon market. A selected number of other regions join in 2045.

4. Departing from the "full offsets hypothesis"

4.1 Restrictions along the "when" dimension

Although OECD regions hope to have an OECD-wide emission trading scheme in 2015, the lack of international policy coordination may slow down the whole process, postponing the establishment of a global carbon market. If this were the case, OECD countries would be required to compensate for the missing trade with additional domestic abatement.

Table 5 reports consumption losses when access to international offsets is delayed over time by 10, 15, 20, or 25 years. Postponing the establishment of an international carbon market increases global macroeconomic costs moderately for delays until 2030-2035, but waiting until 2045 raises the policy bill by about 50%. This is driven by additional losses in OECD regions. Instead, in non-OECD the (moderate) consumption costs are halved, reducing the global penalty. Welfare improvements in these regions are a second-best result, driven by positive technology spillovers, and lower energy prices. They also depend on the assumption that non-OECD countries commit to considerably milder emission reduction objectives compared to OECD.

Table 5: Regional macroeconomic losses of climate policy when the use of international offsets is delayed ("when" dimension).

Consumption losses discounted at 3% discount rate, 2005-2100

	OECD	**Non-OECD**	**World**
Full offsets	1.68%	0.18%	1.07%
from 2030	1.81%	0.11%	1.12%
from 2035	1.90%	0.08%	1.17%
from 2040	2.26%	0.05%	1.37%
from 2045	2.70%	0.08%	1.64%

Negative entries indicate consumption gains

When trade is restricted, alternative and more expensive mitigation options are adopted, driving up compliance costs. To meet the stabilisation target OECD countries rely mostly on two options: contraction of fossil fuel consumption, expansion of investments in energy-saving innovation and low-carbon technologies, such as Carbon Capture and Sequestration (CCS), renewables (Wind and Solar), nuclear power and breakthrough technologies[11].

With limited access to international offsets, OECD regions substantially decrease their demand of all fossil fuels (traditional gas, coal, and oil), oil in particular. The reduced use of oil in OECD countries lowers its international price, benefiting non-OECD regions. This effect is also known as energy market effect, which is one of the possible sources of carbon leakage. A second channel that is not discussed in this paper works through changes in terms-of-trade and international competitiveness of energy-intensive industries[12].

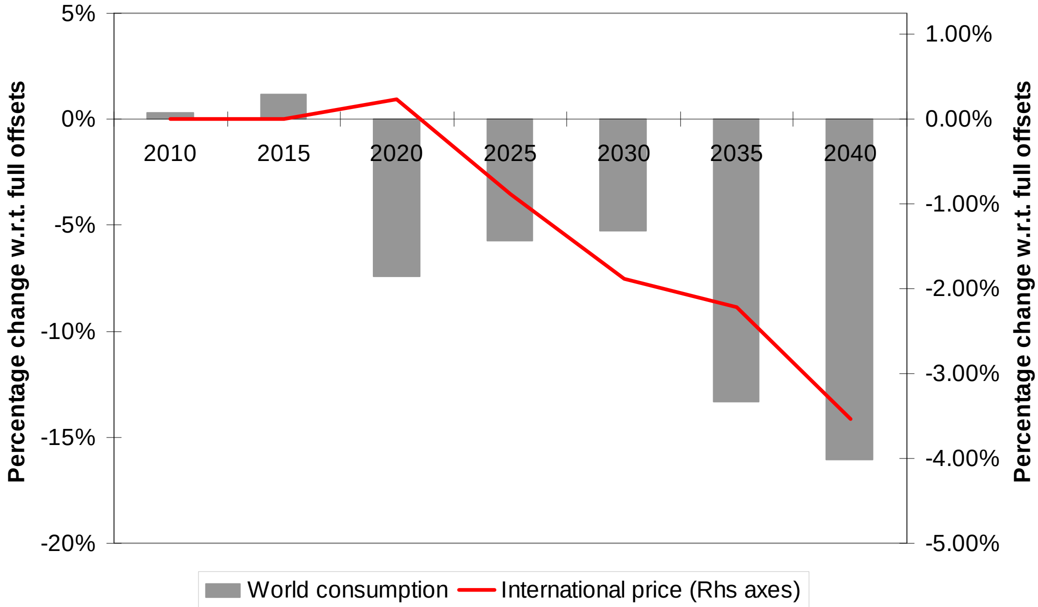
All in all, the contraction of oil demand in OECD countries is only partially offset by carbon leakage in non-OECD, which increases the oil demand by 11% (on average) between 2020 and 2040. Figure 1 shows that in the extreme case of a 2045 delay, these two effects result in a global demand cutback of 16% in 2040. The international price is reduced by almost 4% compared to the case in which full offsets are available. It should be mentioned that most of the oil price reduction occurs when implementing a stabilisation policy, in the full offset case, where the oil price falls by about 30% in 2050 and 70% in 2010, with respect to the baseline. Thus the additional impact of restricting emission trade on the energy prices is relatively contained.

---

[11] We analyse these results for the most stringent case in which trade starts in 2045. The other cases have similar, but smaller magnitude effects.

[12] Burniaux and Oliveira Martins (2000) assessed the relative contribution of each of the two channels and concluded that the non-energy market effect is less important than expected.

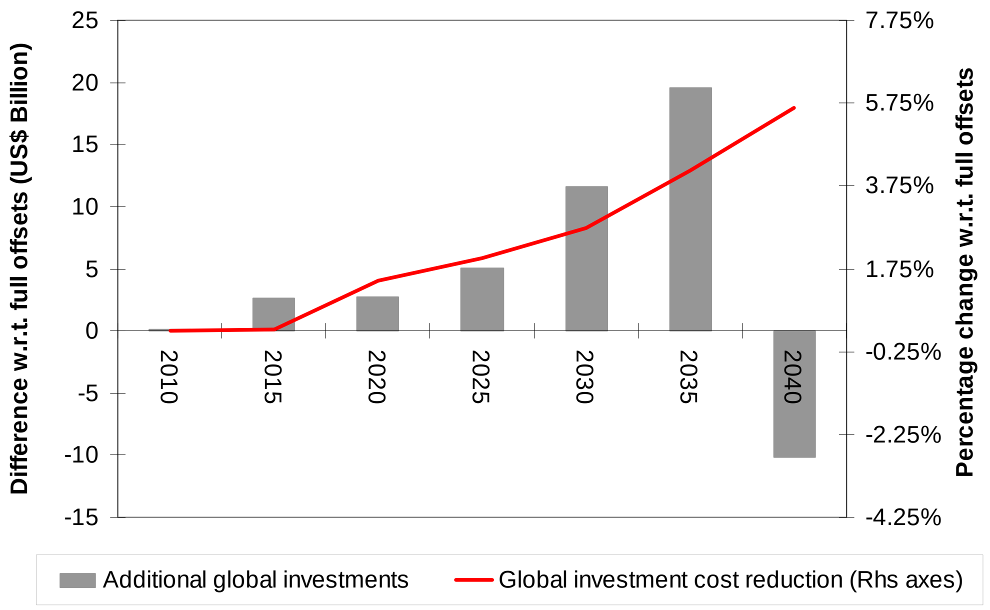
Figure 1: International oil market. Price and consumption when delaying the use of international offsets to 2045



Achieving a tight commitment in the absence of international carbon market requires scaling up investments in innovation and deployment of low-carbon technologies. Since innovation and investments in low-carbon technologies generate positive spillovers, they induce more technological change and thus lower abatement costs in all regions. In other words, the additional costs paid by OECD regions lead to additional benefits in non-OECD.

Figure 2 depicts the global path of investments in wind and solar. As mentioned in Section 2, investment costs in wind and solar decline with global deployment. Learning-By-Doing thus generates international positive spillovers. During the transition period without permit trading (2020-2040), OECD investments in wind and solar are raised to match the more stringent abatement target. Investments in non-OECD initially remain at levels comparable or slightly lower than in the full offsets hypothesis, but eventually increase as well. This pattern is due to the reduction in global investment costs caused by additional investment effort in the OECD. Investments drop below the full offsets case only in 2040, in anticipation of the opening to international offsets in 2045, but they remain higher thereafter. The additional investment cost reduction for wind and solar induced by the trade restriction decreases over time because of the decreasing marginal benefits of investments, but nonetheless remains positive throughout the whole century. Such path dependencies help lower the climate policy costs in the long-term, but require an additional effort in the beginning, that is mostly faced by developed countries.

Figure 2: Wind and solar - when delaying the use of international offsets to 2045



A similar result is observed for investments in energy efficiency R&D, which globally increase throughout the century, but by a larger magnitude during the transition period without emission trading. The global increase is mostly driven by additional investments in OECD countries. Non-OECD countries slightly reduce their R&D effort in the short-run, but increase it after 2035.

4.2 Restrictions along the "how much" dimension

This section assumes that an international carbon market will already be in place in 2020, but with quantitative restrictions on the use of international offsets, mimicking most of the existing and proposed cap-and-trade schemes.

Table 6 illustrates the regional shares of abatement that would be met from international offsets in the absence of any form of market restriction. Without any ceiling, and for this given distribution of allowances, developed countries would find it optimal to buy between 18% and 54% of their abatement on the international market. Already a mild restriction of 20% would be binding for most developed countries, especially in the short-run and in Europe. The United States is right at the limit.

Table 6: Regional shares of abatement met from international carbon market. Net import of permits over total abatement under "full offsets hypothesis"

	USA	Europe	Other OECD
2020	31%	54%	44%
2025	22%	42%	36%
2030	18%	35%	32%
2035	20%	34%	31%
2040	20%	31%	29%
2045	20%	29%	29%

The macroeconomic costs of the stabilisation policy when only up to 20%, 15% or 10% of total abatement in each region can be done with international offsets are reported in Table 7. In terms of global consumption losses, a mild restriction such as 20% creates costs that are comparable to postponing trade to 2030 (1.12% consumption loss). Tighter restrictions (10%) have costs comparable to postponing trade to at least 2035 (1.17% consumption loss).

The dynamics of regional costs depends not only on the interactions between the effects outlined before (energy market and technology spillovers), but also on the trading position of each region. In the short-term, net sellers (non-OECD) tend to lose because of the contraction of the market and, as a consequence, of the carbon price. The non-OECD regions supply is rationed and therefore they emit more. However, they anticipate that after 2045 there will be a lager demand of permits and therefore they still keep emissions below the initial allocation. Throughout the century, limiting trade to 10% of regional abatement increases non-OECD welfare by about 40% because revenue losses on the carbon market are offset by the energy market effects and technology spillovers.

The effect on net buyers (OECD) depends on whether the limit is binding or not. When the limit is binding, the region loses because more expensive abatement options have to substitute for imported credits. This occurs especially in Europe. If the limit is not binding, the region gains because carbon permits are cheaper. This is the case of the US where in 2030 the 20% restriction is not binding (see also Section 3)[13].

[13] It is interesting to note that Buonanno et al. 2000, in the different policy setting of the Kyoto Protocol and with a different model without international technology spillovers found a similar result for the US.

Table 7: Regional macroeconomic losses of climate stabilisation policy when limiting the use of international offsets ("how much" dimension). Consumption losses discounted at 3% discount rate, 2005-2100

	OECD	Non-OECD	WORLD
Full offsets	1.68%	0.18%	1.07%
20%	1.76%	0.14%	1.11%
15%	1.84%	0.12%	1.15%
10%	1.97%	0.11%	1.22%

Negative entries indicate consumption gains

To quantify the contribution of the energy market effect and technology spillovers, we consider three variations of the 15% scenario in which either or both effects are switched off[14]. Table 8 shows the macroeconomic losses of each case expressed in US$ Trillion. Figures indicate that the technology spillover effect is somewhat larger than the energy market effect, though in both cases the efficiency losses are small when compared to the overall policy costs shown in Table 2 by a few percentage points. The reason for this, as noted above, is that the stringent climate stabilisation policy considered in this paper requires a drastic switch of the energy system from a fossil fuel based to a low carbon one even in the case with full access to international offsets. This limits the additional room for reduction in the prices of energy and low carbon fuels when trade is constrained.

The technology spillovers channel is found to be higher in OECD regions. Despite being closer to the technology frontier, developed countries have to comply with a very stringent domestic commitment (especially when trade is limited) that requires fast and major investments in low carbon mitigation options, such as wind and solar. Thus, the gains of equal reduction of investment costs in renewables (given by the assumption of global learning by doing) benefits developed countries more than developing ones. On the contrary, the energy market effect is larger for Non-OECD countries, which are confronted with less demanding mitigation obligations and can procrastinate the consumption of fossil fuels.

[14] Specifically, we ran three additional simulations of the 15% trade restriction case in which we fixed the costs of either fossil fuels or low carbon technologies characterised by spillovers to the values of the full offsets policy scenario.

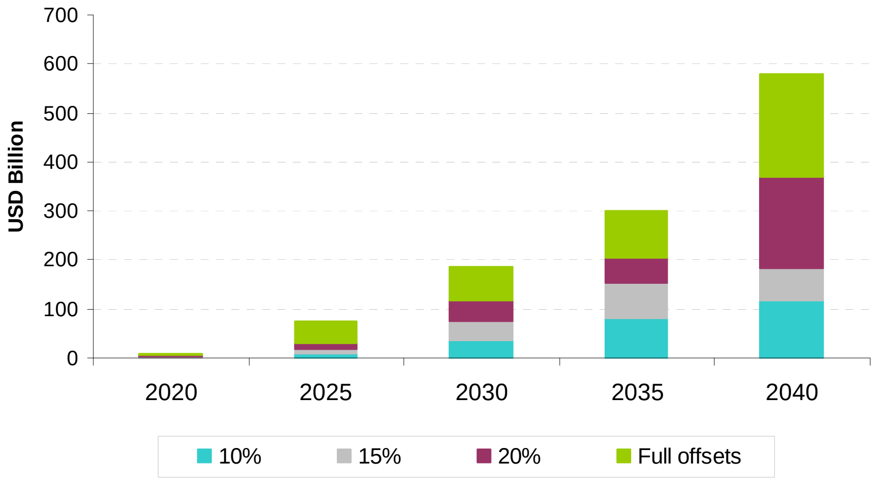
Table 8: Assessing the role of energy market effect and technology spillovers. Consumption losses compared to the 15% case (US$ Trillion)

	OECD	Non-OECD	WORLD
Energy market effect	0.11	0.40	0.51
Technology spillovers	0.88	0.32	1.19
Both	0.97	0.68	1.65

Another prominent argument used to justify ceilings on international offsets is to limit the flows of financial resources from OECD to other regions. The question is whether it is worthy to bear additional economic costs in order to reduce financial outflows. Figure 3 depicts the financial outflows from OECD regions under different restrictions. In the short-term (2020) financial implications of unrestricted trade are small, but they grow very rapidly over time. Already in 2025, the amount spent on the carbon market would equate current OECD expenditure on gas imports. If left unrestricted, the carbon market could lead to very significant flows already in 2040, comparable to what OECD currently spend for oil imports, between US$ 500 and 700 Billion for a low and high oil price scenario, respectively.

Limiting the purchase of international offsets to 10% of total abatement would keep the amount of transferred resources around US$ 100 Billion, though it would generate a global efficiency loss up to 35% in the mid-term. When considering the costs throughout the century, the penalty is lower, about 13%. This reduction is due to the path of technological change, which requires upfront investments but payoff in the long-term, after 2050. A limit to 15% would constrain outflows to US$ 200 Billion, twice as much as the 10% case, but with a significantly smaller penalty (17% until 2050 and 7% until 2100). A further loosening of the trade constraint would marginally alleviate the extra economic loss (8% up to 2050 and 3% in the long-run) but it would not be very effective in controlling monetary transfers. In light of this, the intermediate limit of 15% of abatement to be met via international permits stands out as a reasonable compromise between these two forces.

Figure 3: Carbon market and financial transfers under different quantitative restrictions on the use of international carbon offsets



4.3 Restrictions along the "where" dimension

In the last case, we turn to the situation in which an international carbon market already exists in 2020, but some regions do not take part until 2045. As noted by Frankel (2008), it could be that the eligibility to sell permits is restricted to countries with good international governance ratings, or that commit to invest the revenue in green projects, or that have demonstrated ability to abide to commitments. We analyse the implications of delaying the participation of three groups of developing regions that in the global carbon market would play the role of net sellers: Energy Exporting Regions (Middle East and North Africa and Russia), Developing Asia (China and India) and Rest of World (Latin America and Sub-Saharan Africa).

Excluding either region from the international carbon market has limited effects on global macro-economic costs (Table 9), essentially because others compensate the absence of a seller with increased supply. The only case that leads to a visible additional global penalty is the exclusion of Developing Asia, which supplies more than 50% of the demand of permits. For example, the price of carbon in 2025 would double if Developing Asia were not included in the market, whereas it would increase by only a few percentage points if other regions were to delay. This result stems from the fact that emerging economies such as China and India are assumed to host the largest base of mitigation opportunities. It also reinforces the known argument that any climate policy has to look East to be effective.

Table 9: Regional macroeconomic losses of climate stabilisation policy when selected regions join cap-and-trade in 2045 (“where” dimension). Consumption losses discounted at 3% discount rate, 2005-2100

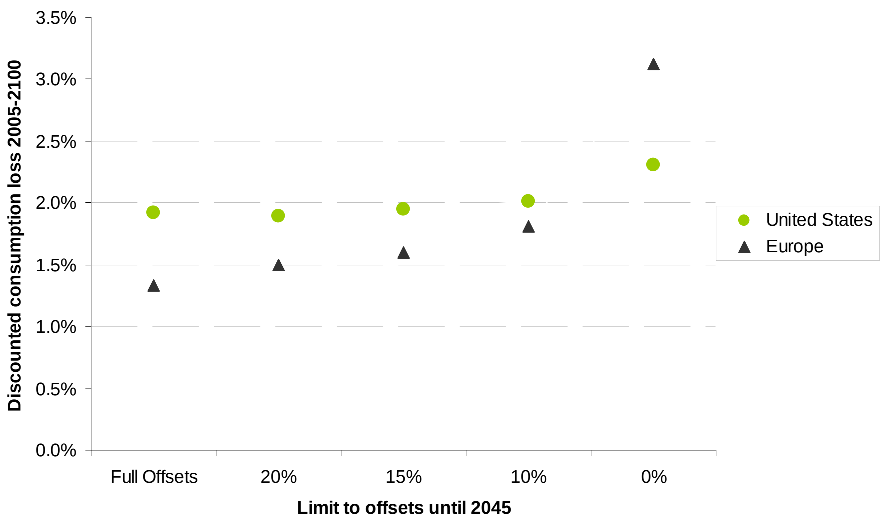
	OECD	Non-OECD	World
Full offsets	1.68%	0.18%	1.07%
DA join in 2045	1.82%	0.12%	1.14%
ROW join in 2045	1.73%	0.16%	1.10%
EEX join in 2045	1.73%	0.17%	1.10%

Negative entries indicate consumption gains

5. Implications for the United States and Europe

This section focuses on the United States and Europe, which have both proposed quantitative and qualitative limits on international offsets. Figure 4 shows macroeconomic costs in the US and Europe when international offsets can be used freely and under different ceilings. Two different behaviours can be detected. For Europe, policy macroeconomic costs are quite sensitive to the tightening of the limit to trade. As shown in Table 6, Europe relies quite significantly on the international carbon market. Complete reliance on domestic abatement would result in a considerable economic cost, with mid-term consumption losses slightly above 3%. A 15% ceiling would induce a penalty of about 20%, though from a lower base compared to the US.

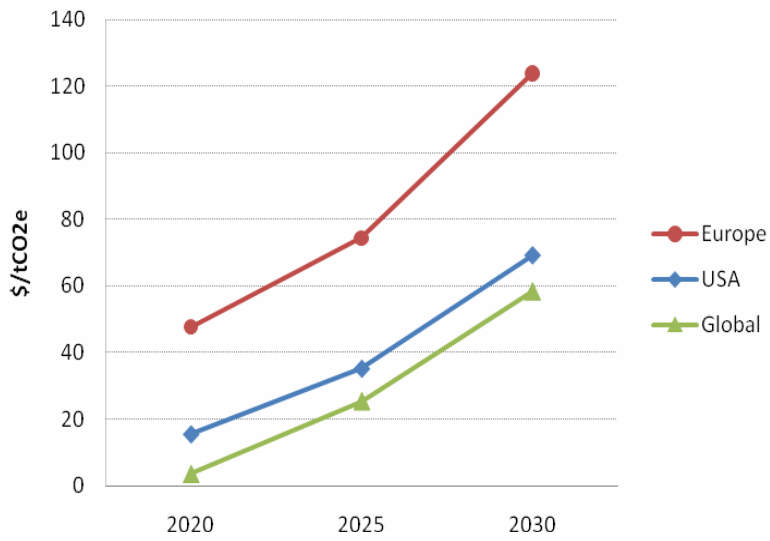
Figure 4: Macroeconomic costs in Europe and United States under different quantitative restrictions on the use of international carbon offsets. Consumption losses discounted at 3% discount rate



The US reports a mild sensitivity to restrictions in offsets, and actually a potential for short-term and mid-term welfare gain for limits of 20% and 15%. A 20% restriction would not be binding. As explained in Section 3, a non-binding ceiling generates benefits because it reduces the carbon price and thus, the expenditure for carbon credits. The 15% restriction is binding, but spillovers and the energy market effects compensate the additional costs, leading to short-term welfare gains and only to a 1% long-term additional penalty. A mild restriction could (slightly) ease the costs of the climate policy in the US, provided all OECD countries adhere to the same trade limit rule. This last condition is important because the US would profit from the reduction in oil prices and in investment costs of low carbon technologies induced by the tighter commitment in the rest of OECD, too. Because equivalent offsets restrictions lead to relatively more abatement in Europe and other OECD countries, they also induce more investments in innovation outside the US. Europe has to comply with a 20% reduction by 2020, therefore it begins to invest in mitigation options earlier.

As for CO_2 prices, limiting the access to the international carbon market implies that marginal abatement costs are not equalised across countries. Permit buyers (sellers) would face a higher (lower) cost of carbon than the price of permits in the full offsets case. For example, a 15% limit on trade would raise the cost of carbon significantly more in Europe than in the US, as shown in Figure 5. The US would have economic benefits from imposing a slightly higher carbon tax and relying less on international offsets, provided Europe and the rest of OECD were also willing to adopt equally stringent (but with a higher impact on marginal costs of abatement) measures.

Figure 5. Marginal cost of carbon in Europe and US for a 15% limit on international offsets until 2045, and global carbon price when the market is not restricted



The 15% constraint is roughly in line with the Senate Bill proposal by Boxer and Kerry to limit the purchase of international offsets to 0.5 GtCO2 a year (half of the one passed in the Waxman-Markey Bill, that in our simulations would not be binding). A constraint between 15 and 10% is also consistent with the upper bound set in the European Emission Trading Scheme (1.6-1.7 billion tons between 2008 and 2020).

6. Summary and conclusions

The use of international carbon offsets in achieving climate stabilisation targets has always been a prominent issue in climate negotiations, but few studies have assessed its role in a second-best setting. This paper fills this gap by studying the macroeconomic and the financial consequences of international offsets when multiple externalities are considered. It provides a numerical evaluation of how different constraints on the size, timing, and participation to an international carbon market affect the macroeconomic costs of climate policy, international financial transfers and the stimulus to carry out innovation.

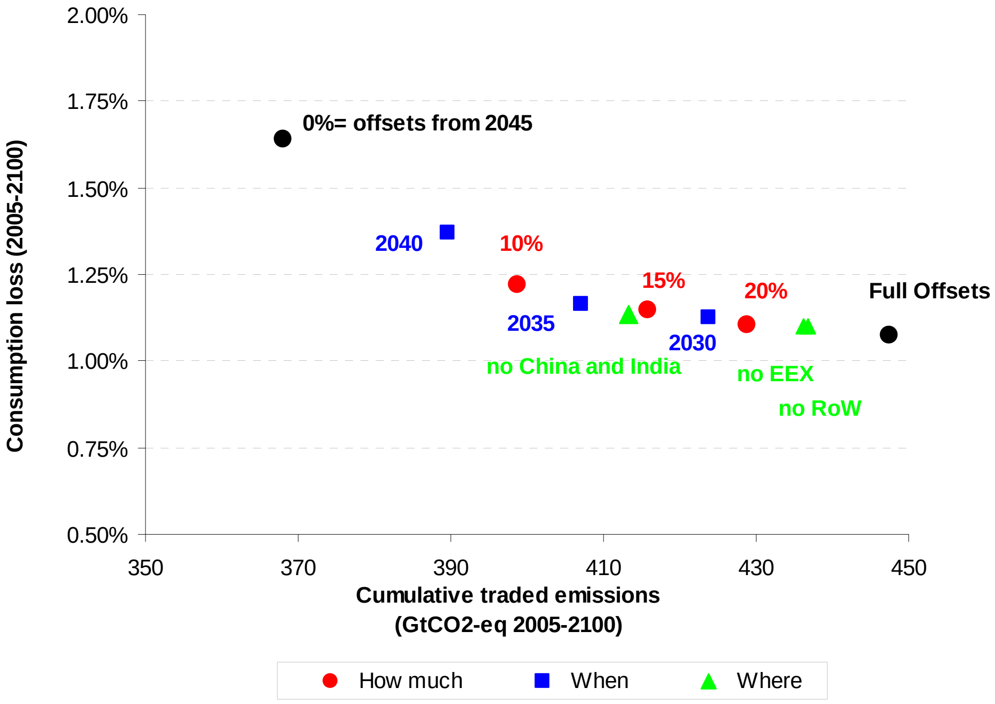
We have shown that for a climate policy entailing deep emission cuts in OECD countries (-90% compared to 2005 in 2050), an unrestricted international carbon market would entail financial transfers that are initially small but that would grow very rapidly, equating today's OECD gas imports in 2025 and today's OECD oil imports in 2040.

Limiting the access to international offsets provides an additional stimulus to innovation and deployment of low carbon technologies, and decreases the consumption of fossil fuels in OECD countries. International spillovers of both knowledge and experience extend the benefits of technological change to non-OECD regions as well. For moderate restrictions on international offsets, we found that technology spillovers and energy market effects can compensate the lower revenue from the carbon market.

Figure 5 summarises the relationship between the size of carbon market and the economic costs of the climate policy. When moving from the full offsets hypothesis to the limiting case of no international offsets until 2045, the costs of the climate policy increases quite significantly, by about 50%. However, the relation between trade limits and policy costs is quite flat for moderate restrictions. A limit of 15% (i.e. 85% of abatement must be achieved domestically) would be comparable to postponing trade between 2030 and 2035 or to exclude the larger seller from trade.

This would result in a slight global efficiency loss. Almost all penalties that arise from trade restrictions are borne by the developed countries, since developing countries are compensated by the positive externalities of technological change and energy market effects.

Figure 5: Carbon market and global macroeconomic costs. Consumption losses discounted at 3% discount rate



Policy costs in Europe are shown to be more sensitive to ceilings than those in the US, especially for the more stringent cases. An upper bound of 15% of abatement to be met via international carbon offsets would somewhat increase the policy costs in Europe (+20%) but actually bring about short-term welfare gains in the US. Such provision is in line with the rules discussed for the third Phase of the European Emission Trading Scheme and with the currently proposed Senate Bill by Boxer and Kerry. Weighting the effects on macroeconomic costs, financial flows, and innovation, our results indicate that a moderate quantitative limit to the use of international offsets, such as the 15% proposed in Europe and in the US, might be a second-best policy recommendation.

6. References

Babiker, M. J. Reilly, L. Viguier (2004) “Is International Emissions Trading Always Beneficial?”, *The Energy Journal*, **25** (2): 33-56

Bennear, L. and R.Stavins (2007) “Second-best theory and the use of multiple policy Instruments”, *Environmental Resource Economics*, **37**: 111–129

Bohm, P. (1999) “International Greenhouse Gas Emissions Trading – with Special Reference to the Kyoto Protocol”, in C. Carraro (ed.), Efficiency and Equity of Climate Change Policy. Dordrecht: Kluwer Academic Publishers

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni (2006) “WITCH: A World Induced Technical Change Hybrid Model,” *The Energy Journal*, Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38

Bosetti, V. C. Carraro, E. Massetti, M. Tavoni. (2008a) "International Energy R&D Spillovers And The Economics Of Greenhouse Gas Atmospheric Stabilization", *Energy Economics* 30 2912-2929

Bosetti, V., C. Carraro, A. Sgobbi, and M. Tavoni (2008b) “Modeling Economic Impacts of Alternative International Climate Policy Architectures: A Quantitative and Comparative Assessment of Architectures for Agreement” Discussion Paper 2008-20, Cambridge, Mass.: Harvard Project on International Climate Agreements, December 2008

Bosetti V., E. De Cian, A. Sgobbi and M. Tavoni (2009) “The 2008 WITCH Model: New Model Features and Baseline”, FEEM Working Paper, 85.2009

Bosetti, V. and J. Frankel (2009) “Global Climate Policy Architecture and Political Feasibility: Specific Formulas and Emission Targets to Attain 460 PPM CO2 Concentrations” Discussion Paper 2009-30, Cambridge, Mass.: Harvard Project on International Climate Agreements, September 2009

Bosetti, V., C. Carraro and M.Tavoni (2009) “Climate Policy After 2012. Technology, Timing, Participation”, *CESifo Economic Studies* **55** (2):235-254

Buonanno, P., C. Carraro, E. Castelnuovo, and M. Galeotti (2000) “Efficiency and Equity of Emission Trading with Endogenous Environmental Technical Change”, in C. Carraro (ed.), Efficiency and Equity of Climate Change Policy. Dordrecht: Kluwer Academic Publishers

Burniaux J, Oliveira-Martins J (2000) “Carbon emission leakages: a general equilibrium view”, OECD Economics Department Working Paper 242, OECD Economics Department

Capoor, K. and P. Ambrosi (2009) “State and Trends of Carbon Market 2009”, The World Bank, Washington D.C., May 2009

Clarke, L., C. Bohringer, and T.F. Rutherford (2009) “International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22”, *Energy Economics*, **31** (2)

Chander, P., Tulkens, H., Van Ypersele, J-P. And Willems, S. (2002) “The Kyoto Protocol: An Economic and Game Theoretic Interpretation”, chapter 6 (pp.98-117) in Kriström, B., Dasgupta P. and Löfgren K.-G. (eds), Economic Theory for the Environment : Essays in Honor of Karl-Göran Mäler, Edward Elgar, Cheltenham

de Sépibus, J. (2008) “Linking the EU Emissions Trading Scheme to JI, CDM and post-2012 International Offsets. A legal Analysis and Critique of the EU ETS and the Proposals for its Third Trading Period,” NCCR TRADE Working paper, No. 18

Driesen, David M. (2003) “Does Emissions Trading Encourage Innovation?”, *Environmental Law Reporter*, 32

Frankel, J. (2008) “An Elaborated Proposal For Global Climate Policy Architecture: Specific Formulas and Emission Targets for All Countries in All Decades,” Chapter 2, forthcoming in Post-Kyoto International Climate Policy, edited by Joe Aldy and Rob Stavins, Cambridge University Press. HPICA DP 08-08. NBER WP 18476

Golombek, R. and M. Hoel (2006) “Second-best Climate Agreements and Technology Policy”, *Advances in Economic Analysis & Policy*, **6** (1)

Golombek, R. and M. Hoel (2008) “Endogenous technology and tradable emission quotas”, *Resource and Energy Economics, Elsevier*, **30** (2): 197-208

Goulder L.H. (1998) “Environmental policy making in a second-best setting”, *Journal of Applied Economics*, **1** (2):279–328

Hourcade, J.C., M. Ha-Doung and F-Lecocq (1999) “Decision making under uncertainty and inertia constraints: sectoral implications of the when flexibility”, *Energy Economics*, 20: 539-56.

IPCC (2007) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., XXX pp.

Karp, L. and J. Lao (2009) “Suggestions for the road to Copenhagen”
http://are.berkeley.edu/~karp/

Jacoby, H D., Babiker, B. H., Paltsev, S., Reilly, J. M. (2008) “Sharing the Burden of GHG Reductions”, MIT Joint Program on the Science and Policy of Global Change, Report No. 167

Jaffe A.B., Newell R.G., Stavins R.N. (2003) “Technological change and the Environment,” in: Karl-Göran M, Jeffrey V (eds) Handbook of environmental economics, vol I. Elsevier Science, Amsterdam, pp 461–516

Jaffe, A., R. Newell and R.Stavins (2005) “A tale of two market failures: Technology and environmental policy”, *Ecological Economics* **54**, 164– 174

Jaffe, J. and R. N. Stavins (2007) "Linkage of Tradable Permit Systems in International Climate Policy Architecture." Discussion Paper 08-07, Harvard Project on International Climate Agreements, Belfer Center for Science and International Affairs, Harvard Kennedy School, September 2008

Lipsey, R.G. and K. Lancaster (1956) “The General Theory of Second Best”, *The Review of Economic Studies*, **24** (1): 11–32

Luderer, G., V. Bosetti, J. Steckel, H. Waisman, N. Bauer, E. De Cian, M. Leimbach, O. Sassi, M. Tavoni (2009). “The Economics of Decarbonization – Results from the RECIPE model intercomparison”, RECIPE Working paper, available online at http://www.pik-potsdam.de/recipe

McKibbin, W.J., Shackleton, R., Wilcoxen, P.J. (1999) “What to expect from an international system of tradable permits for carbon emissions”, *Resource and Energy Economics*, 21, 319-346

Paltsev S., J. M. Reilly, H. D. Jacoby, A. C. Gurgel, G. E. Metcalf, A. P. Sokolov and Jennifer F. Holak (2008) “Assessment of U.S. Cap-and-Trade Proposals”, MIT Global Change Joint Program Report 146

Paltsev, S., J.M. Reilly, H.D. Jacoby and J.F. Morris (2009) “The Cost of Climate Policy in the United States”, Appendix C. MIT Global Change Program. Report 173

Richels, R.G., T.F. Rutherford, G.J. Blanford, and L. Clarke (2007) “Managing the Transition to Climate Stabilisation”, AEI-Brooking Joint Center Working Paper No. 07-01

Victor, D. (2007) “Fragmented carbon markets and reluctant nations: implications for the design of effective architectures”, in *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, edited by Aldy, J. and Stavins, R. N., pp. 133-160, Cambridge University Press, Cambridge, UK

Wara, M.W. and D.G. Victor (2008) “A realistic policy on International carbon offsets”, PSED Working paper no. 74

Wigley, T., Richles, R., Edmonds, J.A. (1996) “Economic and Environmental Choices in the Stabilisation of Atmospheric CO2 concentrations”, *Nature*, **379** (6562), 240-43

Weyant, J.P., Hill, J.N. (1999) “Introduction and overview”, *Energy Journal Special Issue*
The Costs of the Kyoto Protocol: A Multi-Model Evaluation, vii-xliv

Appendix. The WITCH model

Full details on the WITCH model can be found in Bosetti et al. (2007) and Bosetti et al. (2009). This appendix provides a brief summary of the model. It recalls the most distinguishing features related to environmental, economic, and technology externalities, and the game-theoretic set-up.

Brief model description

WITCH is a dynamic optimal growth model (“top-down”) with a “bottom-up” representation of the energy sector. It can be classified as a hybrid model. The geographical coverage is global and world regions are grouped into twelve macro-regions sharing economic, geographic, and energy similarities. These regions are USA (United States), WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJANZ (Canada, Japan, New Zealand), TE (Transition Economies), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), CHINA (China and Taiwan), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean).

The WITCH model includes a range of technology options that describe the use of energy and power generation. Different fuels can be used for electricity generation and final consumption: coal, oil, gas, uranium, and biofuels. Electricity can be generated using a series of traditional fossil fuel-based technologies and carbon-free options. Fossil fuel-based technologies include natural gas combined cycle (NGCC)and fuel oil and pulverised coal (PC) power plants. Coal-based electricity can also be generated using integrated gasification combined cycle production with carbon capture and sequestration (CCS). Low carbon technologies include hydroelectric and nuclear power, wind turbines and photovoltaic panels (Wind&Solar), and a breakthrough technology. A second backstop option is included in final consumption and it is meant to represent an alternative to oil in transportation such as hydrogen and advanced biofuels. The model features endogenous technical change in the energy sector in the form of both Learning-By-Researching and Learning-By-Doing.

The game-theoretic set-up makes it possible to capture the non-cooperative nature of international relationships. Climate change is the major global externality, but other economic externalities induce free-riding behaviours and strategic interactions. The model can produce two different solutions. The cooperative solution is globally optimal because it maximises global social welfare and it internalises environmental and economic externalities. It represents a first-best optimum. The decentralised, or non-cooperative solution is strategically optimal for each given region (Nash equilibrium), but it does not internalise externalities. It represents a second-best optimum. The Nash equilibrium is computed as an open-loop Nash equilibrium. It is the outcome of a non-cooperative, simultaneous, open membership game with full information.

The remaining of the Appendix describes in detail the environmental, technology, and economic externalities.

The climate externality

Long-lived Greenhouse Gases become perfectly mixed with other gases in the world atmosphere. No matter where the initial source of emission is located, it will affect global GHG concentrations and eventually global mean temperature and climate. For this reason, emissions from any source, anywhere in the world, give rise to a global negative externality. Long-lived GHGs remain in the atmosphere from decades to centuries. Present emissions build up over past emissions and increase the concentrations for very long temporal horizons. The WITCH model includes carbon cycle and climate modules that describe the international and intertemporal dimension of the global externality of GHG emissions.

A climate module describes the physical relationship between GHG emissions, radiative forcing, and temperature. Temperature relative to pre-industrial levels increases through augmented radiative forcing of different GHGs. Radiative forcing in turn depends on CO_2 and non-CO_2 atmospheric concentrations. Stoichiometric coefficients are applied to the use of fossil fuels to derive related CO_2 emissions. Among non-CO_2 gases, emissions of methane (CH_4), Nitrous dioxide (N_2O), short-lived fluorinated gases, (SLF, HFCs with lifetimes under 100 years) and long-lived fluorinated (LLF, HFC with long lifetime, PFCs, and SF6) are explicitly modelled. We also distinguish SO_2 aerosols, which have a cooling effect on temperature.

A reduced-form damage function, *D(n,t)*, describes a relationship between regional damages and global mean temperature increase above pre-industrial levels, *T(t)*. The quadratic functional form makes it possible to account for both gains and losses:

$$D(n,t) = \theta_{1,n} T(t) + \theta_{2,n} T(t)^2 \qquad \text{(A1)}$$

Physical impacts can be translated into monetary units by including the damage function into the final production function. Equation (A2) expresses climate change damages as fraction of final output, *YGROSS*:

$$YNET(n,t) = \frac{YGROSS(n,t)}{\Omega(n,t)} \tag{A2}$$

where

$$\Omega(n,t) = 1 + D(n,t)$$

International knowledge spillovers for energy enhancing R&D

Investments in energy R&D build up a stock of knowledge (*HE*) that improves overall energy efficiency. The energy knowledge stock augments the quantity of final energy services (*ES*) that can be provided per unit of physical energy (*EN*), according to a Constant Elasticity formulation:

$$ES(n,t) = \left[\alpha_H HE(n,t)^{\rho_{ES}} + \alpha_{EN} EN(n,t)^{\rho_{ES}}\right]^{1/\rho_{ES}} \tag{A3}$$

Learning processes during knowledge accumulation or deployment of advanced technologies will not be confined within the boundaries of investing countries, but knowledge and expertise are likely to spill, with some lag, worldwide. Therefore, the generation of new ideas is characterised by an innovation possibility frontier that exhibits both intertemporal and international spillovers. At each point in time, new ideas (*Z*) are produced using a Cobb-Douglas combination between domestic investments ($I_{R\&D}$), the domestic stock of knowledge (*HE)*, and the foreign stock of knowledge (*SPILL)*:

$$Z(n,t) = a\, I_{R\&D}(n,t)^b\, HE(n,t)^c\, SPILL(n,t)^d \tag{A4}$$

The contribution of foreign knowledge is not immediate, but it depends on the interaction between two components shown in equation (A5). The first term describes countries' absorptive capacity whereas the second one captures the distance of each region from the technology frontier. The technology frontier is represented by the stock of knowledge in high-income countries (USA, WEURO, EEURO, KOSAU, and CAJANZ):

$$SPILL(n,t) = \frac{HE(n,t)}{\sum_{HI} HE(n,t)} \left(\sum_{HI} HE(n,t) - HE(n,t)\right) \tag{A5}$$

The flow of new ideas (Z) adds to the previously cumulated stock and generates the total amount of knowledge available to each country at each point in time:

$$HE(n,t+1) = Z(n,t) + HE(n,t)(1-\delta_{R\&D}) \tag{A6}$$

International experience spillovers for wind and solar

WITCH represents the diffusion of technologies and experience in some niche technologies such as Wind&Solar. The rapid and recent development of wind turbines and photovoltaic panels has led to a reduction in investment costs. A learning curve in wind and solar technologies captures the empirically-observed relationship between declining investments costs and installed capacity, an effect which is known as Learning-By-Doing. Investment costs in new Wind and Solar capital, $SC(n,t)$, decrease with the world installed capacity, $\sum_n K_j(n,t)$:

$$SC_j(n,t+1) = B_j(n) \cdot \sum_n K_j(n,t)^{-\log_2 PR_j}$$

We assume full technology spillover: investments in additional capacity by virtuous regions drive down investment costs worldwide within a model time period, which corresponds to five years. The progress ratio, PR, defines the speed of learning.

International knowledge and experience spillovers in breakthrough technologies

The WITCH model includes two backstop technologies. These are innovative technologies with low or zero carbon emissions that are currently not commercialised and that necessitate dedicated innovation investments to become economically competitive and available in large supplies. For the purpose of modelling, a backstop technology can be seen of as a compact representation of a portfolio of advanced technologies that would become available before a few decades. The costs of these technologies are modelled with a two-factor learning curve. The unit cost of each backstop technology, $P_{tec,t}$, evolves over time with technology deployment, $CC_{tec,t}$ and the accumulation of a dedicated knowledge stock, $R\&D_{tec,t}$:

$$\frac{P_{tec,T}}{P_{tec,0}} = \left(\frac{R\&D_{tec,T-2}}{R\&D_{tec,0}}\right)^{-c} * \left(\frac{CC_{tec,T}}{CC_{tec,0}}\right)^{-b} \tag{A7}$$

The stock of *R&D* accumulates with the perpetual rule and with the contribution of international knowledge spillovers, *SPILL*:

$$R\&D_{tec,T+1} = R\&D_{tec,T}(1-\delta) + IR\&D_{tec,T}{}^{\alpha} \quad SPILL_{tec,T}{}^{\beta} \qquad \text{(A8)}$$

The two exponents are the Learning-by-Doing index ($-b$) and the Learning-by-Researching index ($-c$) and they define the speed of learning. The learning ratio *lr* is the rate at which costs decline each time the cumulative capacity doubles, while *lrs* is the rate at which costs decline at the doubling of the knowledge stock.

We set the initial prices of the backstop technologies at roughly 10 times the 2005 price of commercial equivalents. The cumulative deployment of the technology is initiated at an arbitrarily low value, 1,000twh and 1,000EJ for the electric and non-electric, respectively. Backstop technologies are assumed to be renewable in the sense that the fuel cost component is negligible. The backstop for power generation is assumed to operate at load factors comparable with those of baseload power generation.

Backstops substitute linearly nuclear power in the electric sector, and oil in the non-electric one. Once backstop technologies become competitive, their uptake is not immediate and complete, but rather we assume a transition/adjustment period. These penetration limits capture the inertia in the system, as large deployment of these advanced technologies will require investment and re-organisation in energy infrastructure. At each point in time, the upper limit is equal to 5% of energy produced by other technologies and the backstop itself in the previous period.

International energy markets

The markets of exhaustible resources are assumed to be integrated and they are represented as an international market for each fuel. International prices depend on fossil fuels extraction, which in turn is driven by regional consumption.

The model considers four non-renewable fuels: coal, crude oil, natural gas, and uranium. Their costs follow a long-term trend that reflects their exhaustibility. Resource prices are calculated endogenously using a reduced-form cost function that allows for non-linearity in both the depletion effect and in the rate of extraction. Assuming competitive markets, the domestic price $P_f(n,t)$ is equal to the marginal cost and it depends on the cumulative quantity of fossil fuels extracted, *Qf (n,t)*:

$$P_f(n,t) = \chi_f(n) + \pi_f(n)\left[Q_f(n,t)/\overline{Q}_f(n,t)\right]^{\psi_f(n)} \tag{A9}$$

where $\chi_f(n)$ is a regional markup, $\overline{Q}_f$ is the amount of total resources at time *t*, and $\pi_f(n)$ measures the relative importance of the depletion effect. Cumulative extraction depends on the demand for fossil fuels of all 12 regions in the model:

$$Q_f(n,t) = Q_f(n,t-1) + \sum_{n=1}^{12} \chi_{f,extr}(n,t) \tag{A10}$$

Cumulative extraction depends on the amount of fuel *f* extracted in region *n* at time *t*, $X_{f,extr}(n,t)$.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
http://ideas.repec.org/s/fem/femwpa.html
http://www.econis.eu/LNG=EN/FAM?PPN=505954494
http://ageconsearch.umn.edu/handle/35978
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2010

GC	1.2010	Cristina Cattaneo: Migrants' International Transfers and Educational Expenditure: Empirical Evidence from Albania
SD	2.2010	Fabio Antoniou, Panos Hatzipanayotou and Phoebe Koundouri: Tradable Permits vs Ecological Dumping
SD	3.2010	Fabio Antoniou, Panos Hatzipanayotou and Phoebe Koundouri: Second Best Environmental Policies under Uncertainty
SD	4.2010	Carlo Carraro, Enrica De Cian and Lea Nicita: Modeling Biased Technical Change. Implications for Climate Policy
IM	5.2010	Luca Di Corato: Profit Sharing under the threat of Nationalization
SD	6.2010	Masako Ikefuji, Jun-ichi Itaya and Makoto Okamura: Optimal Emission Tax with Endogenous Location Choice of Duopolistic Firms
SD	7.2010	Michela Catenacci and Carlo Giupponi: Potentials and Limits of Bayesian Networks to Deal with Uncertainty in the Assessment of Climate Change Adaptation Policies
GC	8.2010	Paul Sarfo-Mensah and William Oduro: Changes in Beliefs and Perceptions about the Natural Environment in the Forest-Savanna Transitional Zone of Ghana: The Influence of Religion
IM	9.2010	Andrea Boitani, Marcella Nicolini and Carlo Scarpa: Do Competition and Ownership Matter? Evidence from Local Public Transport in Europe
SD	10.2010	Helen Ding and Paulo A.L.D. Nunes and Sonja Teelucksingh: European Forests and Carbon Sequestration Services : An Economic Assessment of Climate Change Impacts
GC	11.2010	Enrico Bertacchini, Walter Santagata and Giovanni Signorello: Loving Cultural Heritage Private Individual Giving and Prosocial Behavior
SD	12.2010	Antoine Dechezleprêtre, Matthieu Glachant and Yann Ménière: What Drives the International Transfer of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data
SD	13.2010	Andrea Bastianin, Alice Favero and Emanuele Massetti: Investments and Financial Flows Induced by Climate Mitigation Policies
SD	14.2010	Reyer Gerlagh: Too Much Oil
IM	15.2010	Chiara Fumagalli and Massimo Motta: A Simple Theory of Predation
GC	16.2010	Rinaldo Brau, Adriana Di Liberto and Francesco Pigliaru: Tourism and Development: A Recent Phenomenon Built on Old (Institutional) Roots?
SD	17.2010	Lucia Vergano, Georg Umgiesser and Paulo A.L.D. Nunes: An Economic Assessment of the Impacts of the MOSE Barriers on Venice Port Activities
SD	18.2010	ZhongXiang Zhang: Climate Change Meets Trade in Promoting Green Growth: Potential Conflicts and Synergies
SD	19.2010	Elisa Lanzi and Ian Sue Wing: Capital Malleability and the Macroeconomic Costs of Climate Policy
IM	20.2010	Alberto Petrucci: Second-Best Optimal Taxation of Oil and Capital in a Small Open Economy
SD	21.2010	Enrica De Cian and Alice Favero: Fairness, Credibility and Effectiveness in the Copenhagen Accord: An Economic Assessment
SD	22.2010	Francesco Bosello: Adaptation, Mitigation and "Green" R&D to Combat Global Climate Change. Insights From an Empirical Integrated Assessment Exercise
IM	23.2010	Jean Tirole and Roland Bénabou: Individual and Corporate Social Responsibility
IM	24.2010	Cesare Dosi and Michele Moretto: Licences, "Use or Lose" Provisions and the Time of Investment
GC	25.2010	Andrés Rodríguez-Pose and Vassilis Tselios (lxxxvi): Returns to Migration, Education, and Externalities in the European Union
GC	26.2010	Klaus Desmet and Esteban Rossi-Hansberg (lxxxvi): Spatial Development
SD	27.2010	Massimiliano Mazzanti, Anna Montini and Francesco Nicolli: Waste Generation and Landfill Diversion Dynamics: Decentralised Management and Spatial Effects
SD	28.2010	Lucia Ceccato, Valentina Giannini and Carlo Gipponi: A Participatory Approach to Assess the Effectiveness of Responses to Cope with Flood Risk
SD	29.2010	Valentina Bosetti and David G. Victor: Politics and Economics of Second-Best Regulation of Greenhouse Gases: The Importance of Regulatory Credibility
IM	30.2010	Francesca Cornelli, Zbigniew Kominek and Alexander Ljungqvist: Monitoring Managers: Does it Matter?
GC	31.2010	Francesco D'Amuri and Juri Marcucci: "Google it!" Forecasting the US Unemployment Rate with a Google Job Search index
SD	32.2010	Francesco Bosello, Carlo Carraro and Enrica De Cian: Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage

SD	33.2010	Enrica De Cian and Massimo Tavoni: The Role of International Carbon Offsets in a Second-best Climate Policy: A Numerical Evaluation

(lxxxvi) *This paper was presented at the Conference on "Urban and Regional Economics" organised by the Centre for Economic Policy Research (CEPR) and FEEM, held in Milan on 12-13 October 2009.*