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## Summary

In this paper we use the hybrid integrated model WITCH to quantify and analyze the investments and financial flows stimulated by a climate policy to stabilize Greenhouse Gases concentrations at 550ppm $CO_2$-eq at the end of the century. We focus on investments to decarbonize the power sector and on investments in knowledge creation. We examine the financial flows associated with the carbon market and the implications for the international trade of oil. Criticalities in investment requirements will emerge when coal power plants with carbon capture and sequestration and nuclear power plants are deployed around 2020-2040, both in high and low income regions. Investments in energy related R&D increase sharply and might cause stress in the short term. However, the transition to a low-carbon world, although costly, appears to be manageable from a financial point of view. In particular, R&D financial needs can easily be accommodated using revenues from the carbon market, which is expected to eventually become more important than the oil market in terms of traded value.

**Keywords:** Climate Change, Mitigation, Carbon Finance, Emission Trading, Energy Investments

**JEL Classification:** Q01, Q43, Q54, O32, O11

*This paper is part of the research work being carried out by the Sustainable Development Programme at the Fondazione Eni Enrico Mattei. The authors wish to thank Carlo Carraro and FEEM Sustainable Development Unit seminar participants for valuable comments and suggestions.*

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# INVESTMENTS AND FINANCIAL FLOWS INDUCED BY CLIMATE MITIGATION POLICIES


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4 December 2009


Abstract

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# 1. Introduction

Over the past two centuries emissions of Greenhouse Gases (GHGs) have increased sharply due to sustained economic growth, low cost of fossil fuels, deforestation and other land use changes. Growing above the natural absorption capacity of the earth eco-systems, GHGs emissions have been accumulated in the atmosphere reaching concentrations unprecedented for at least a million years. GHGs are indispensable because they keep the earth warm enough to support life as we know it: without GHGs the infrared solar radiation would escape the atmosphere and the earth temperature would be below 0°C. However, excessive concentrations lead to global warming and to a worldwide alteration of climate.[1]

The assessment of the social and economic impacts of moderate climate change (between 1.5°C – 3.5°C) is extremely complicated and far from being resolved. There will be gainers – those who live in relatively cold places – and losers – those who live in low-latitude, already warm poor countries. The aggregate balance is still not clear, but it will not necessarily be negative. A substantial increase of world mean temperature (at +5°C for example) would instead very likely generate irreversible, potentially catastrophic climate disruptions. This concern is shared by virtually all the scientific community and it is at the core of the motivations that support international action to stabilize GHGs concentrations at safe levels (Weitzman, 2009).

Until recently, the focus of studies on optimal mitigation strategies has been on overall macroeconomic costs. Often overlooked are instead the implications of mitigation policies in terms of investments needed to support the required low-carbon transformations of the economies. Despite being two sides of the same coin, costs and investments inform on two very different aspects of climate policy and should not be confused.

Investments are expenditures to increase productive capital. Investments imply a financial transfer from one agent to another, from one sector of the economy to another sector, or from one generation to the next. If investments are re-distributed among capital assets that have the same productivity (i.e. that yield the same output per unit of investment), there is a re-distribution of resources from one sector to another, but the level of macroeconomic activity is not affected. Macroeconomic costs arise only when investments are redistributed from more productive uses to less productive uses. This loss of productivity generates a lower level of output, which is the true net cost for the economy as a whole.

Unfortunately, it is frequent to find studies that do not distinguish clearly between investments and costs. In particular, investments are often referred to as costs of the climate policy (see for instance: IEA, 2008, p. 487; Russ *et al*, 2009; European Commission, SEC(2009) 1172, p. 4, Table 2; a notable exception is UNFCCC, 2007).

Pure financial flows are transfers that do not result in productive capital investments. In the case of climate policy, transactions on the carbon markets, both at domestic and international level, are financial flows. Also revenues from carbon taxes are financial flows.

There is now a wide agreement on the fact that, not counting environmental benefits, mitigation policy indeed diverts resources from less expensive to more expensive ways of generating and using energy. Advocates of win-win solutions to climate change dispute this result and support the idea that, by reducing inefficiencies of the economy other than the environment, climate policy might actually have overall macroeconomic benefits. This will probably be true for some sectors and in some periods of time but very few studies show that this would hold at aggregate level and over a long time horizon. Therefore, climate policy is almost unanimously considered to be costly over the long-run.[2]

[1] See work of the Working Group I of the IPCC (i.e. Solomon *et al*, 2007) for a thorough treatment of the science of climate change.
[2] The Energy Modelling Forum 22 has produced estimates of mitigation costs at global and regional level using a variety of models and under different assumptions on participation and timing of abatement efforts (Clarke *et al*, 2010).

While the literature on mitigation policy costs has grown considerably during the past fifteen years, the implication of climate policy on investment patterns and on financial flows are still not widely explored. This paper tackles exactly this issue. It contributes to a recent literature whose main concern is to estimate the investments needed to finance the low-carbon transformation of the economies. A key question in this literature is whether the amount and timing of investments are such to require a specific government intervention to support the private sector.

We focus here on mitigation policy alone, leaving aside considerations on the financial needs for adaptation to climate change. Our work is grounded on scenarios of long-term climate policy produced by the hybrid integrated assessment model WITCH (World Induced Technical Change Hybrid), developed at Fondazione Eni Enrico Mattei (FEEM).[3] In particular, we look at financial requirements to transform the power sector and to scale-up Research and Development (R&D) activities in the energy sector. Investments in the power sector are endogenous in the model, as it is overall electricity and energy demand and fuels prices. Regarding R&D activities, the focus of WITCH on endogenous technical change makes possible to provide original insights on their dynamics.

We assess investment trajectories on a time horizon that stretches up to 2050, a year now widely used to set intermediate stabilization targets, and we assess when criticalities will likely emerge along this time path. In order to draw policy insights, we compare the required financial efforts to previous large scale investment and R&D projects.

Other very relevant questions concern the size of the financial flows associated to carbon pricing and the implications of climate policy on the international crude oil market. Climate policy will basically consist in establishing a price for carbon, a commodity that has not been priced so far and thus “used” in excess. The price of carbon can be imposed either by a tax, or it will emerge from the exchange of emissions allowances in a cap-and-trade scheme, or by a mix of these approaches. In any case, carbon will become a major world commodity and will generate enormous financial flows, at both domestic and international level. At the same time, the international crude oil market will tend to disappear because oil will be used minimally in a low-carbon world. Financial transactions associated to the oil market will tend to shrink even further because oil price will likely diminish from the present level. This study will assess the implications of this historical change.

The mitigation policy scenario that we use aims at stabilizing GHGs concentrations at 550 parts per million (ppm) of $CO_2$-equivalent ($CO_2$-eq) at 2105. This level of concentrations will generate, as an IPCC best estimate, a temperature change of 2.9°C, approximately one degree higher than the 2°C goal advocated in the international climate policy arena (IPCC AR4, WG I, Ch 10, Table 10.8; see Meehl *et al*, 2009). It must be considered that in order to attain the 2°C target at least with a fifty percent chance, it would be necessary to stabilize concentrations at about 450 ppm $CO_2$-eq over the same time horizon, when concentrations have already reached about 430 ppm $CO_2$-eq. This is politically extremely ambitious and technically almost impossible to achieve (see Carraro and Massetti, 2009). We thus focus on the 550 ppm $CO_2$-eq concentration level (which corresponds roughly to a 450 $CO_2$ only level), a more sensitive climate policy target.[4]

Compared to the large number of analyses on the cost of climate policy, there are relatively few studies that assess the implications of stabilization policy for investments and financial transfers (see Table 1 for a summary). The first attempt to quantify financial requirements of mitigation policies is probably from the UNFCCC secretariat.

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For a recent study of mitigation policy costs at European level see the RECIPE Project (Edenhofer *et al* 2009). For an analysis of mitigation policy costs using the WITCH model see for example Bosetti *et al* (2009c).

[3] See Bosetti, *et al* (2006), Bosetti, Massetti and Tavoni (2007) and Bosetti *et al* (2009e) for a detailed description of the WITCH model.

[4] The level of $CO_2$-eq concentrations was 430 ppm in 2005. If we consider that from 1995 to 2005, $CO_2$ concentrations alone have grown at the pace of 1.9 ppm per year, we see how little room there is for further emissions. In order to achieve the 450 ppm target the world as a whole must bring GHGs emissions to zero in little more than a decade or to rely on highly speculative technologies that would be capable of generating net negative emissions on a very large scale.

**Table 1 Summary of models**

| ID | Model | Horizon | Policy Target | Endogenous demand | Reference |
|---|---|---|---|---|---|
| UNFCCC | ENV-LINKAGE/OECD | 2100 | 550 ppm CO2 eq | no | UNFCCC (2007) |
| RECIPE | IMACLIM-R/REMIND-R/WITCH | 2100 | 500-550 ppm CO2 eq[†] | yes | Edenhofer et al. (2009) |
| IEA | World Energy Model | 2030 | 450 ppm CO2 eq<br>550 ppm CO2 eq | no | IEA (2008) |
| IPTS-JCR | GEM3/POLES | 2050 | Multiple[‡] | yes | Russ et al. (2009) |
| McKinsey | Global GHG Abatement Cost Curve v2.0[*] | 2030 | 480 ppm CO2 eq | no | McKinsey (2009) |
| WITCH | WITCH | 2100 | 550 ppm CO2-eq | yes | |

**Notes:**

(*) The Global GHG Abatement Cost Curve v2.0 is not a model, but rather a measure of technical opportunities to reduce emissions of GHGs at a cost of up to 60€ per tCO2 eq of avoided emissions.

(†) RECIPE considers a default stabilization target of 450 ppm CO2; depending on assumptions about emissions of other GHGs, this corresponds to overall GHG concentrations of 500–550 ppm CO2 eq.

(‡) The target of the "Central Scenario" is defined on the basis of a set of 4 indicators: the group of developed countries have a -30% target compared to 1990 in 2020, whereas the emissions of developing countries in 2020 are limited to 20% below the baseline emissions.

In 2007 the UNFCCC has defined a reference and a mitigation scenario for GHGs emissions using a variety of models and projections.[5] The report defined both investment flow as the initial (capital) spending for a physical asset and financial flow as an ongoing expenditure related to climate change mitigation or adaptation that does not involve investment in physical assets. In particular, it estimated that additional investment and financial flows of USD 200–210 billion would be necessary to return $CO_2$-eq emissions to current levels (2004) by 2030.[6] This path of emissions is coherent with a stabilization target of 550 ppm $CO_2$-eq at the end of the century. Focusing on the energy sector, the mitigation scenario requires less investment in the production of fossil fuels and associated facilities, and substantial shifts of investments within the power sector. Under the mitigation scenario, investment in energy supply infrastructure is projected to be USD 695 billion in 2030, USD 67 billion (9 per cent) less than under the reference scenario. Power supply requires more than USD 432 billion of investment under the mitigation scenario, USD 7 billion (1.6 per cent) less than the reference scenario. Most of the increased investment is for large-scale deployment of CCS from 2020 onwards. Capital expenditure in fossil fuel supply would require USD 263 billion under the mitigation scenario. Finally, more than half of all the energy investment needed worldwide is in developing countries due to their rapid economic growth.

In the recent RECIPE study on low-carbon mitigation scenarios, conduced by three European research institutes, including FEEM with the WITCH model, investments in mitigation technologies to achieve a 450 ppm $CO_2$ concentration target would increase by USD 1200 billion by the middle of the century, while investments in conventional fossil fuels based sources of energy generation would be reduced by USD 300 to 550 billion with respect to the reference scenario (Edenhofer *et al*, 2009). The largest slice of the pie would go to finance the deployment of renewable energy sources and to support the construction of power plants equipped with carbon capture and storage (CCS). The strength of the RECIPE project is that the estimates of additional investments on harmonized scenarios are produced by three well established integrated assessment models which encompass a rich set of options to describe economic and energy system dynamics, over a century-long time horizon. These three models are "optimization models", in the sense that the dynamics of

[5] For the reference scenario, Energy-related $CO_2$ emissions were derived from the IEA World Energy Outlook (WEO) 2006; non-$CO_2$ emissions projections from the United States Environmental Protection Agency (US EPA) extrapolated to 2030; current $CO_2$ emissions due to land use, land-use change and forestry, and industrial process $CO_2$ emissions projections from the World Business Council for Sustainable Development (WBCSD). The ENV-Linkage model of the OECD is used to produce the reference and mitigation scenarios for investment and financial flows. The mitigation scenario consists of the energy-related $CO_2$ emissions of the IEA WEO 2006 beyond the alternative policy case scenario; the non-$CO_2$ emission reductions possible at a cost of less than USD 30 per tonne of $CO_2$-eq as estimated by the US EPA; potential increases in sinks due to agriculture and forestry practices and potential industrial process $CO_2$ emission reductions estimated by WBCSD. UNFCCC secretariat (2007).

[6] Recently, the UNFCCC secretariat (2008) provided an update to the paper estimating that additional investment and financial flows needed are about 170 per cent higher, mainly due to higher projected capital costs, especially in the energy sector. UNFCCC secretariat (2008). "Investment and financial flows to address climate change: An update. Technical paper." Available at http://unfccc.int/resource/docs/2008/tp/07.pdf

the economy, and in particular of the energy sector, are the outcome of a throughout evaluation of different investment alternatives across sectors and time. Energy demand is not exogenous in these models, but rather an endogenous choice which reflects the relative cost of energy, especially when carbon emissions are priced severely in the ambitious stabilization scenarios. Higher energy costs trigger incentives to save energy and to reduce the amount of investments needed in the energy sector, compensating higher expenditure for more expensive energy technologies.

For 550 ppm $CO_2$-eq target (thus similar to the 450 $CO_2$ only target of RECIPE) the International Energy Agency (IEA, 2008) estimates additional investments in the power sector to be equal to USD 1.2 trillion between 2010 and 2030. Investments in more efficient buildings and end-use technologies to increase energy efficiency amount to 3.0 trillion. The IEA also explores the more ambitious 450 ppm $CO_2$, although it warns that the scale of the challenge to obtain this concentrations target is immense and it is uncertain whether it is technically achievable (IEA, 2008, p. 48). The amount of investments in the power sector to achieve this stricter target is equal to USD 3.6 trillion and 5.7 trillion needed to increase energy efficiency. The largest fraction of these investments, according to both scenarios, is required between 2020 and 2030. These results are obtained using the World Energy Model (WEM) of the IEA, a large scale mathematical modelling tool which draws information from observed trends in the past to project energy demand until 2030. Projections of investments are derived from the projected energy demand. The WEM is not a general equilibrium model and does not represent endogenously feedbacks from the energy system to the macro-economy.

The Institute for Prospective Technological Studies (IPTS) of the European Commission's Joint Research Centre (JRC) has recently published a study that explores investment scenarios in the energy sector that are consistent with a long term 2°C target (Russ *et al*, 2009).[7] The European Commission has based on this study its recent communications on climate change policy (SEC(2009) 101, COM(2009) 475 and SEC(2009) 1172). Five global mitigation scenarios have been analysed, which can lead to the 2°C objective. Under all scenarios in order to achieve the temperature target by 2020 developed countries as a group reduce their emissions by 30 per cent below 1990 levels and developing countries as a group limit emissions to 15 per cent to 30 per cent below the reference scenario. The scenarios were developed using a soft-linking multi-sector general equilibrium model GEM-E3[8] and POLES a world energy sector simulation model.[9] Macroeconomic implications were derived until 2020, while energy sector scenarios have been extended to 2050. Interestingly, world cumulative investments in the power sector at 2020 do not increase and they decrease if cumulated up to 2030. The same pattern arises for the EU-27. For the larger group of all developed countries cumulative investments slightly increase in both periods; on the contrary, they decrease in developing countries. At first counter-intuitive, especially if compared to the IEA scenarios, these results are instead fully rational and bear an important insight: even if the average cost of new installed capacity in the power sector increases when carbon-intensive power plants are replaced by low-emissions ones, overall electricity demand shrinks faster, driven by energy efficiency improvement, and the overall investments in the power sector decline. It is hard to interpret instead the overall costs of the energy sector, estimated to be equal to 666 billion Euros, at 2005 prices, over the period 2013-2020. It is possible that these are investments rather than "true" costs. Nonetheless, it is not clear what would cause such increased spending, especially considering that the power sector would not require additional resources. Probably, the model predicts higher investments for the transport sector or an increase in efficiency in industrial and residential uses. Unfortunately, the lack of a detailed description of the methodology used to estimate total investments does not allow a thorough assessment of the whole set of European Commission position papers that use this study as a reference.

McKinsey (2009) uses a peculiar approach based on GHGs abatement cost curves to represent abatement opportunities costing less than Euro 60 per tonne of $CO_2$ (at 2005 prices). Remaining below this threshold, according to McKinsey, it is possible to abate GHGs emission 35 per cent with respect to 2030 or 70 per cent with respect to their business-as-usual scenario if aggressive action is implemented to adopt each single

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[7] The report is at the basis of the January 2009 European Commission Communication titled "Towards a comprehensive climate change agreement in Copenhagen".
[8] For a description of the model: http://www.gem-e3.net/download/GEMmodel.pdf .
[9] Two models are soft-linked when they maintain they are run separately and the outcome of one is used as an input of the other in an iterative process that stops at convergence.

abatement opportunity. This is in line with a concentration target of roughly 480 ppm $CO_2$-eq. In this study abatement costs are defined as annualized costs of different abatement measures in a given year per tonne of carbon saved, with respect to the business-as-usual technology. Comparing the cost of different abatement technologies allows to allocate investments efficiently. The McKinsey definition of costs is the technology-level equivalent of the definition of macroeconomic cost we adopted in this paper. However, McKinsey costs do not include transaction costs as well as dynamic macro-economic effects which might be non-negligible especially for many low cost, diffused, emissions reductions opportunities. Investments represent the additional capital expenditure in the year when the abatement action is taken, relative to the business-as-usual investment. Annual investments in abatement measures would be Euro 320 billion in 2015, Euro 530 billion in 2020 and Euro 810 billion in 2030 (1.3 per cent of global GDP in 2030). Whereas the investments in 2030 for developed countries only represents 0.5-1.0 per cent of GDP, in developing countries this ratio increases to 1.2-3.5 per cent.[10] The 60 per cent of additional investments will be located in developing countries.

Compared to the previous studies of investment trajectories under climate policy, this work stands out for a number of reasons.

First, the WITCH model represents economic growth and technological progress dynamics with a greater realism than the other models used so far to assess investment dynamics. Economic growth is largely endogenous in WITCH and responds to the incentives to accumulate capital for productive uses. Technological progress in the energy sector is also endogenous in WITCH and it allows to study the incentive to invest in knowledge creation under climate policy.

Second, WITCH is a truly dynamic model in which investment decisions are taken with perfect foresight. This means for example that carbon prices expected in the future affect present investment decisions in power plants. Also, the future benefit of a larger knowledge stock to invent energy efficient technologies is anticipated and motivates early investments in R&D.[11]

Third, energy sector dynamics are fully endogenous. Final energy demand depends on the (endogenous) relative prices of capital, labor and energy inputs. This is a key feature because it generates endogenously the optimal demand of energy under climate policy, unlike other models that need to assume an exogenous path for energy demand. Energy demand is also indirectly affected by endogenous investments in R&D to increase end-use energy efficiency. The optimal mix of power plants is endogenous and it is defined by a long-term assessment of the convenience to invest in different technologies. Fuels' prices (oil, natural gas, coal and uranium) are endogenous and increase as cumulative extraction increases.

Fourth, WITCH has a peculiar game-theoretic structure that allows to model non-cooperative interactions among countries. In the Reference scenario, twelve world regions interact non-cooperatively on the environment (GHGs emissions), fossil fuels, energy R&D, and on learning-by-doing in renewables. In the climate policy scenario regions are assumed to cooperate on the environment and a world carbon market is introduced to equate marginal abatement costs globally. Investment decisions in one region affect investment decisions in all other regions, at any point in time.[12]

WITCH is basically a game-theoretic, energy-focussed, variant of the well-known Ramsey-Cass-Koopmans optimal neoclassical growth model, widely used in economic growth theory to study investment dynamics trough time and across sectors.

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[10] The overall worldwide cost of abatement technologies is projected to be about Euro 150 billion per year by 2030; this figure does not include transaction and program costs of around Euro 40-200 billion generating a total cost Euro 190-350 billion (less than 1% GDP). Global GDP is projected around USD 90 trillion by 2030, and the report use and exchange rate of 1.5 USD/EUR thought the analysis.

[11] There is not uncertainty and it is possible to perfectly foresee the environment – in terms of economic growth, population, price of inputs – in which investments decisions will be taken.

[12] For an analysis of the incentives to participate in and the stability of international climate coalitions with WICTH see (Bosetti *et al*, 2009b).

The major pitfall of WITCH is the low detail in non-electric energy technologies. In particular, WITCH lacks a detailed set of end-use energy technologies and does not distinguishes among transport and residential energy uses. Accordingly, we cannot study investment dynamics in the non-electric sector.

A final word of caution is necessary to interpret our findings. WITCH – as all other Integrated Assessment Models – is designed to produce scenarios and not forecasts. Investments scenarios are certainly accurate and the model is sufficiently well calibrated to produce a picture of the energy sector that, in the Reference scenario, is very close to the short term energy outlooks of the IEA and of the Energy Information Administration (Massetti and Parrado, 2009). However, the aim of the model is to show the major forces at play and how investment dynamics change when climate policy is introduced. This increases our understanding of how economies would optimally respond to climate policy.

We start presenting a Reference scenario in which we assume that during the next century there will be no climate policy. In Section 3 and 4 the Reference scenario will be used to investigate the changes in the optimal mix of investments in the power sector and in R&D induced by climate policy. In Section 5 we present scenarios that show how climate policy marks the rise of carbon finance and the decline of fossil fuels markets.

## 2. From Carbon Intensive to Carbon-Free Energy Systems

### *2.1. A Quick Overview of the WITCH Model*

WITCH – World Induced Technical Change Hybrid – is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate damages (Bosetti *et al.* 2006, 2009e; Bosetti, Massetti and Tavoni, 2007).

It is a hybrid model because it combines features of both top-down and bottom-up modelling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom-up like description of the energy sector. WITCH's top-down framework guarantees a coherent, fully intertemporal allocation of investments, including those in the energy sector.

World countries are aggregated in twelve regions on the basis of geographic, economic and technological vicinity (see the Appendix for more detail on the regional aggregation) which interact strategically on global externalities: greenhouse gases, technological spillovers, a common pool of exhaustible natural resources.

WITCH contains a detailed representation of the energy sector, which allows the model to produce a reasonable characterization of future energy and technological scenarios and an assessment of their compatibility with the goal of stabilizing greenhouse gases concentrations. In addition, by endogenously modelling fuel prices (oil, coal, natural gas, uranium), as well as the cost of storing the $CO_2$ captured, the model can be used to evaluate the implication of mitigation policies on the energy system in all its components.

In WITCH emissions arise from fossil fuels used in the energy sector and from land use changes that release carbon sequestered in biomasses and soils. Emissions of $CH_4$, $N_2O$, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) and $SO_2$ aerosols, which have a cooling effect on temperature, are also identified. Since most of these gases are determined by agricultural practices, the modelling relies on estimates for reference emissions, and a top-down approach for mitigation supply curves.[13]

[13] Reducing emissions from deforestation and degradation (REDD) is estimated to offer sizeable low-cost abatement potential. WITCH includes a baseline projection of land use $CO_2$ emissions, as well as estimates of the global potential and costs for reducing emissions from deforestation, assuming that all tropical forest nations can join an emission

A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHGs concentrations. WITCH is also equipped with a damage function that provides the feedback on the economy of global warming. However, in this study we exclude the damage function and we take the so-called "cost-minimization" approach: given a target in terms of GHGs concentrations in the atmosphere, we produce scenarios that minimize the cost of achieving this target.

Endogenous technological dynamics are a key feature of WITCH. Dedicated R&D investments increase the knowledge stock that governs energy efficiency. Learning-by-doing curves are used to model cost dynamics for wind and solar capital costs. Both energy-efficiency R&D and learning exhibit international spillovers. Two backstop technologies – one in the electricity sector and the other in the non-electricity sector – necessitate dedicated innovation investments to become competitive. In line with the most recent literature, the costs of these backstop technologies are modelled through a so-called two-factor learning curve, in which their price declines both with investments in dedicated R&D and with technology diffusion.

The base year is 2005 for calibration; all monetary values are in constant 2005 USD. The WITCH model uses market exchange rates for international income comparisons.

**Table 2 Economic variables and major indicators trends in the Reference and Policy scenarios.**

| | Reference Scenario | | | | | | Policy Scenario | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 |
| Population (billions) | | | | | | | | | | | | |
| World | 6.5 | 6.9 | 7.7 | 8.3 | 8.8 | 9.2 | 6.5 | 6.9 | 7.7 | 8.3 | 8.8 | 9.2 |
| OECD | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 |
| Non OECD | 5.4 | 5.8 | 6.5 | 7.1 | 7.6 | 8.0 | 5.4 | 5.8 | 6.5 | 7.1 | 7.6 | 8.0 |
| Gross World Product (trillions) | | | | | | | | | | | | |
| World | 44 | 53 | 75 | 102 | 133 | 169 | 44 | 53 | 74 | 100 | 130 | 162 |
| OECD | 35 | 40 | 51 | 62 | 74 | 86 | 35 | 40 | 51 | 62 | 72 | 83 |
| Non OECD | 10 | 13 | 24 | 39 | 59 | 83 | 10 | 13 | 24 | 38 | 58 | 80 |
| Total Primary Energy Supply (EJ) | | | | | | | | | | | | |
| World | 429 | 474 | 577 | 675 | 760 | 831 | 429 | 455 | 498 | 518 | 498 | 467 |
| OECD | 206 | 226 | 256 | 277 | 290 | 300 | 206 | 213 | 220 | 217 | 197 | 175 |
| Non OECD | 223 | 249 | 321 | 398 | 469 | 531 | 223 | 242 | 278 | 301 | 301 | 292 |
| Electricity Demand (TWH) | | | | | | | | | | | | |
| World | 17,954 | 20,308 | 27,092 | 34,930 | 43,315 | 51,867 | 17,954 | 19,209 | 22,751 | 26,487 | 29,851 | 33,736 |
| OECD | 10,159 | 11,215 | 13,560 | 15,755 | 17,856 | 19,894 | 10,159 | 10,427 | 11,638 | 12,937 | 14,139 | 15,609 |
| Non OECD | 7,795 | 9,093 | 13,532 | 19,175 | 25,459 | 31,973 | 7,795 | 8,782 | 11,113 | 13,550 | 15,712 | 18,127 |
| Energy Intensity of Output (index, base year 2005) | | | | | | | | | | | | |
| World | 1.00 | 0.92 | 0.80 | 0.68 | 0.59 | 0.51 | 1.00 | 0.88 | 0.69 | 0.53 | 0.40 | 0.30 |
| OECD | 1.00 | 0.95 | 0.84 | 0.74 | 0.66 | 0.58 | 1.00 | 0.90 | 0.73 | 0.59 | 0.46 | 0.36 |
| Non OECD | 1.00 | 0.82 | 0.58 | 0.44 | 0.34 | 0.28 | 1.00 | 0.80 | 0.51 | 0.34 | 0.23 | 0.16 |
| Carbon Intensity of Energy (index, base year 2005) | | | | | | | | | | | | |
| World | 1.00 | 1.00 | 1.03 | 1.06 | 1.09 | 1.12 | 1.00 | 0.98 | 0.95 | 0.84 | 0.69 | 0.55 |
| OECD | 1.00 | 1.00 | 1.02 | 1.04 | 1.07 | 1.09 | 1.00 | 0.97 | 0.90 | 0.77 | 0.61 | 0.45 |
| Non OECD | 1.00 | 1.00 | 1.03 | 1.07 | 1.10 | 1.14 | 1.00 | 1.00 | 0.98 | 0.89 | 0.75 | 0.61 |

## *2.2. The Reference Scenario*

In the Reference scenario we assume that there is no policy to reduce global warming. Countries behave non-cooperatively on the global commons.

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trading system and have the capacity to implement REDD programs. However, avoided deforestation is not a source of emissions reductions in the version of the model that we used for this study.

Total primary energy demand grows over the whole first half of the century in the Reference scenario, fuelled by population and economic growth (Table 2) and by abundant, relatively inexpensive, fossil fuels (Table 3). Most of the increment of energy demand is expected to come from Non OECD countries, in particular from fast-growing Asian emerging economies. Electricity demand grows at a faster pace than total primary energy supply, revealing a long-term increment of both the absolute and relative weight of the power sector in satisfying energy needs.

**Table 3 Fossil fuels, emissions and climate trends in the Reference and Policy scenarios.**

| | **Reference Scenario** | | | | | | **Policy Scenario** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 |
| Coal Consumption (EJ) | | | | | | | | | | | | |
| World | 122 | 167 | 262 | 351 | 427 | 491 | 122 | 146 | 179 | -218 | 104 | 28 |
| OECD | 54 | 72 | 99 | 116 | 127 | 133 | 54 | 58 | 59 | 37 | -2 | -43 |
| Non OECD | 68 | 95 | 163 | 234 | 301 | 358 | 68 | 88 | 119 | -256 | 106 | 71 |
| Oil Consumption (EJ) | | | | | | | | | | | | |
| World | 158 | 181 | 222 | 253 | 277 | 294 | 158 | 179 | 207 | 193 | 141 | 87 |
| OECD | 90 | 99 | 110 | 115 | 116 | 116 | 90 | 98 | 103 | 84 | 55 | 30 |
| Non OECD | 68 | 82 | 112 | 139 | 161 | 178 | 68 | 81 | 103 | 109 | 85 | 58 |
| Natural Gas Consumption (EJ) | | | | | | | | | | | | |
| World | 92 | 112 | 136 | 153 | 163 | 167 | 92 | 111 | 127 | 121 | 97 | 74 |
| OECD | 47 | 54 | 60 | 63 | 63 | 62 | 47 | 54 | 58 | 52 | 39 | 29 |
| Non OECD | 45 | 58 | 76 | 90 | 100 | 106 | 45 | 56 | 69 | 69 | 57 | 45 |
| Price of Fossil Fuels | | | | | | | | | | | | |
| Coal /$ / Short Ton) | 54 | 55 | 57 | 59 | 63 | 67 | 54 | 55 | 56 | 58 | 59 | 61 |
| Oil ($ / Barrel) | 60 | 62 | 72 | 87 | 106 | 129 | 60 | 66 | 77 | 88 | 92 | 89 |
| Natural Gas ($ / Cubic Feet) | 0.0077 | 0.0073 | 0.0080 | 0.0093 | 0.0111 | 0.0134 | 0.0077 | 0.0073 | 0.0080 | 0.0091 | 0.0102 | 0.0111 |
| $CO_2$ Emissions From Fossil Fuels (Gton$CO_2$) | | | | | | | | | | | | |
| World | 29 | 32 | 40 | 48 | 55 | 62 | 29 | 30 | 32 | 29 | 23 | 17 |
| OECD | 14 | 15 | 18 | 19 | 21 | 22 | 14 | 14 | 13 | 11 | 8 | 5 |
| Non OECD | 15 | 17 | 22 | 28 | 35 | 40 | 15 | 16 | 18 | 18 | 15 | 12 |
| GHG Emissions (Gton$CO_2$-eq) | | | | | | | | | | | | |
| World | 46 | 49 | 58 | 68 | 78 | 86 | 46 | 47 | 48 | 45 | 39 | 33 |
| OECD | 16 | 18 | 21 | 22 | 24 | 25 | 16 | 16 | 16 | 13 | 10 | 7 |
| Non OECD | 29 | 31 | 38 | 46 | 54 | 62 | 29 | 31 | 32 | 32 | 29 | 27 |
| Concentrations of $CO_2$ (ppm) | 380 | 391 | 417 | 449 | 484 | 524 | 380 | 391 | 413 | 433 | 447 | 454 |
| Concentrations of GHG (ppm $CO_2$-eq) | 427 | 444 | 484 | 534 | 593 | 660 | 427 | 443 | 475 | 504 | 526 | 540 |
| Temperature (°C above pre-industrial level) | 0.76 | 0.88 | 1.14 | 1.42 | 1.72 | 1.89 | 0.76 | 0.88 | 1.13 | 1.39 | 1.62 | 1.74 |

Although still voracious in total energy demand, the economies become more energy efficient, according to the Reference scenario. In particular, the contraction of the energy intensity of output is stronger in Non OECD countries, which start from relatively high inefficiencies. Carbon intensity of energy is increasing in both OECD and Non OECD countries, due to a growing use of coal in power generation. Coal remains the cheapest option to fuel power plants for the whole century and the gap with the other fossil fuels increases as time goes by (see Table 3). Accordingly, the share of coal over total fossil fuels demand increases from 33 per cent in 2005 to 52 per cent in 2050 (see Table 3).

The large expansion of total primary energy supply, and the relatively faster expansion of coal – the fuel with the highest content of carbon per unit of energy – explains the continued growth of $CO_2$ emissions from fossil fuels. The absence of any policy to contain $CO_2$ emissions from other sectors explains the overall expansion of $CO_2$ concentrations from 380 ppm to 524 ppm: an average increment of 2.88 ppm per year, substantially higher than the average 1.99 ppm per year from 1995 to 2005 (IPCC, AR4; see Forster *et al* 2007). As a consequence temperature increases 1.9 °C above the pre-industrial (Table 3).[14]

## *2.3. The Policy Scenario*

In the Policy scenario GHGs concentrations are forced to remain below 550 ppm $CO_2$-eq at the end of the century. The global pattern of emissions imposed is the result of a cost-benefit solution of the model under the assumption of a world social planner. Climate policy is assumed to be stringent from 2010. GHGs emissions peak in 2020 at 48 Gton $CO_2$-eq; emissions from fossil fuels also peak in 2020 and then decline by 40 per cent with respect to 2005 in 2050 and by 72 per cent with respect to the Reference scenario.

The policy tool is a global cap-and-trade scheme in which allowances are distributed according to the contraction-and-convergence (CC) rule: in 2010 permits are first distributed in proportion to present emissions and then progressively converge to a full equal-per-capita allocation scheme in 2050. Banking and borrowing of emissions allowances are not allowed, but there is no restriction to international trade of permits[15]. We name this policy scenario *550 ppm CC*.

We work in an ideal framework in which we assume full immediate co-operation among countries and a globally efficient allocation of abatement effort. Despite offering an optimistic view of future international climate policy and carbon markets, with these assumptions we avoid overly complex scenarios and we are able to present a benchmark case against which more realistic policy and market settings can be assessed.[16]

Table 2 shows that the *550 ppm CC* scenario strengthens the efficiency improvements of the Reference scenario and reverts the trend of carbon intensity of energy. Energy efficiency is a major area of action to cut GHGs emissions, especially in the first decades. However, the decarbonization is a necessity and more costly investments have to be realized.

Total primary energy supply declines sharply with respect to the Reference scenario and in 2050 it remains almost unchanged with respect to 2010 after peaking in 2030. Oil and natural gas consumption decline quickly, both in OECD and Non OECD regions, with respect to the Reference scenario and with respect to the base year. The use of coal declines in the first decade and then it increases due to the expansion of coal power plants with CCS. In fact, coal – thanks to CCS – is the only fossil fuel not to decline with respect to present consumption levels.

Climate policy is costly according to WITCH. Investments are necessarily directed towards more expensive technologies, energy efficiency investments and the necessary input reallocation drive the economies away from their most productive resource allocation choices. Discounted global costs are equal to 3 per cent of world GDP, 2.6 per cent for OECD economies and 3.5 per cent for Non OECD economies.

[14] In the Reference scenario GHGs concentrations in the atmosphere reaches 998ppm CO2-eq in 2100, with a temperature increase above the pre-industrial level of 3.75°C.

[15] For the consequences of introducing banking see Bosetti, Carraro and Massetti (2009a). Scenarios with restrictions to trade of carbon permits are presented in Section 4.

[16] It must be noted, however, that climate architectures which contemplate delayed actions or limits to key low-carbon technologies will, with high probability, jeopardize the achievement of the 550 ppm target (Edenhofer et al, 2009; Clarke et al, 2010).

## 3. Transforming the Power Sector

It is often believed that mitigation policies will require a much higher level of investments in the power sector (Table 1). In fact, zero or low-carbon generation technologies have investment costs per unit of installed capacity higher than the traditional coal or gas fired power plants that they are meant to replace. Were all the electricity demand of the Reference scenario to be supplied by low-carbon technologies, the total amount of investments in the power sector would certainly increase. However, this is not necessarily true. In fact, one of the cheapest ways to reduce carbon emissions is to increase overall energy efficiency, reducing also electricity demand with respect to the Reference scenario (Table 2). There are thus two forces at play: more technologically advanced power plants will increase the investment cost per unit of installed capacity, but at the same time overall installed capacity will decline as a result of contraction in electricity demand. We find these effects to be roughly equivalent at global level. As a result, the financial requirements of the power sector do not change significantly when climate policy is implemented (Table 4).

**Table 4**

**(a) Investment as % of total investment by type**

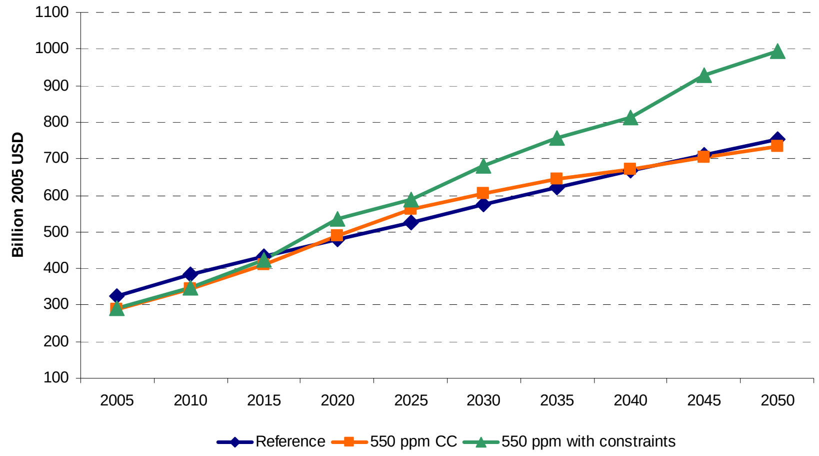
| year | Reference scenario | | | 550 ppm CC scenario | | |
|---|---|---|---|---|---|---|
| | Final Good | Power sector | Energy R&D | Final Good | Power sector | Energy R&D |
| 2005 | 96.46 | 3.46 | 0.08 | 96.78 | 3.11 | 0.11 |
| 2030 | 97.07 | 2.85 | 0.04 | 96.75 | 3.10 | 0.05 |
| 2050 | 97.58 | 2.34 | 0.02 | 97.28 | 2.53 | 0.03 |

**(b) Cumulative total investment by region, 2005-2050: 550 ppm CC - Reference scenario (Billion 2005 USD)**

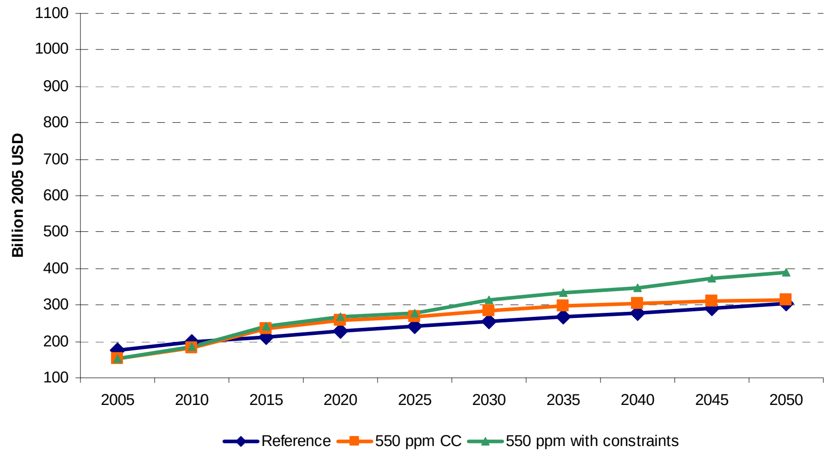
| | 2005-2010 | 2010-2020 | 2020-2030 | 2030-2040 | 2040-2050 | Total 2005-2030 | Total 2030-2050 | Total 2005-2050 |
|---|---|---|---|---|---|---|---|---|
| USA | -39 | -47 | -583 | -2043 | -4603 | -669 | -6646 | -7315 |
| EUROPE | 3 | 25 | -361 | -1390 | -3085 | -333 | -4475 | -4808 |
| Other OECD | -14 | -10 | -135 | -748 | -1715 | -159 | -2463 | -2622 |
| **Total OECD** | **-50** | **-31** | **-1080** | **-4180** | **-9403** | **-1161** | **-13583** | **-14744** |
| China | -36 | -285 | -543 | -1681 | -3401 | -864 | -5082 | -5945 |
| Transition Economies | -21 | -60 | -53 | -95 | -602 | -133 | -697 | -830 |
| Other Non OECD | -59.03 | -461.19 | -1254.55 | -4401.13 | -8844.94 | -1774.77 | -13246.07 | -15020.84 |
| **Total Non OECD** | -59 | -461 | -1255 | -4401 | -8845 | -1775 | -13246 | -15021 |
| **Total World** | **-116** | **-805** | **-1850** | **-6177** | **-12848** | **-2771** | **-19025** | **-21796** |

The fact that financial requirements of the power sector do not change significantly suggests that investing in a low-carbon power sector is perfectly feasible from a macroeconomic standpoint. Financial resources needed to transform electricity generation will not crowd out investments in other sectors, at least in the long-run. The competition for funds will not be between the power sector and other sectors, but rather inside the power sector, between low-carbon and fossil-fuels electricity generation technologies. Forward looking investors, with perfect information, realize that investments in coal fired power plants – which have an expected lifetime of about forty years – are risky due to the high price of carbon that will emerge around 2050 (Figure 6). Accordingly, they decide to wait and invest in low-carbon electricity generation projects as soon as they become available. They also decide to reduce investments because they perfectly anticipate that the demand of electricity will decline as a consequence of climate policy. The behavior of these forward looking agents, despite being a caricature of real-world investors, suggests that the resources invested in the power sector will depend both on the cost of new technologies and on the power sector size. Therefore, models that do not represent autonomous re-adjustment of electricity demand over-estimate the amount of investments needed in the power sector.

(a) World investment in the power sector, 2005-2050




(b) Investment the power sector in OECD countries, 2005-2050




(c) Investment the power sector in Non OECD countries, 2005-2050

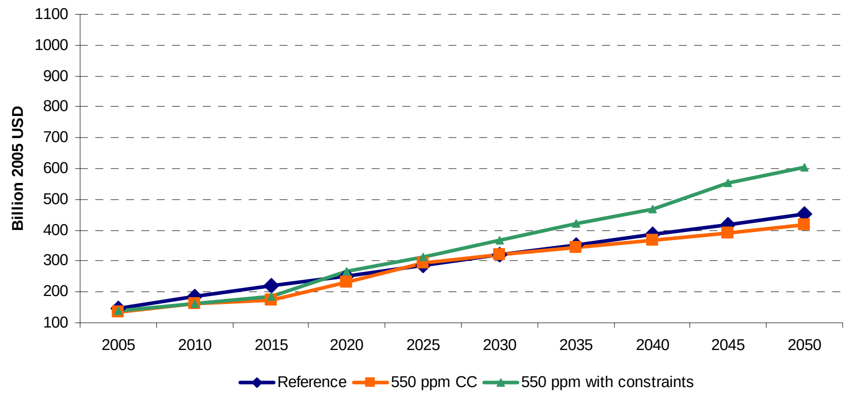



**Figure 1 Total investment in the power sector: World, OECD and Non OECD countries, 2005-2050.**

The fact that climate policy does not change significantly the allocation of resources towards the power sector is confirmed by an analysis of the investment flows direction (see Table 4). The balance between investments in power and non-power capital is practically unaltered in the *550 ppm CC* scenario with respect to the Reference scenario, with the power sector absorbing about 3 per cent of total investments. A radical change is instead necessary to finance R&D in new technologies to decarbonize energy supply and to increase energy efficiency. The massive increment of R&D spending required by a stringent mitigation policy deserves a careful analysis to which we devote Section 4.

Although cumulative global investments in the power sector remain unchanged, some important changes occur in the distribution across time, across power generation technologies and across regions.

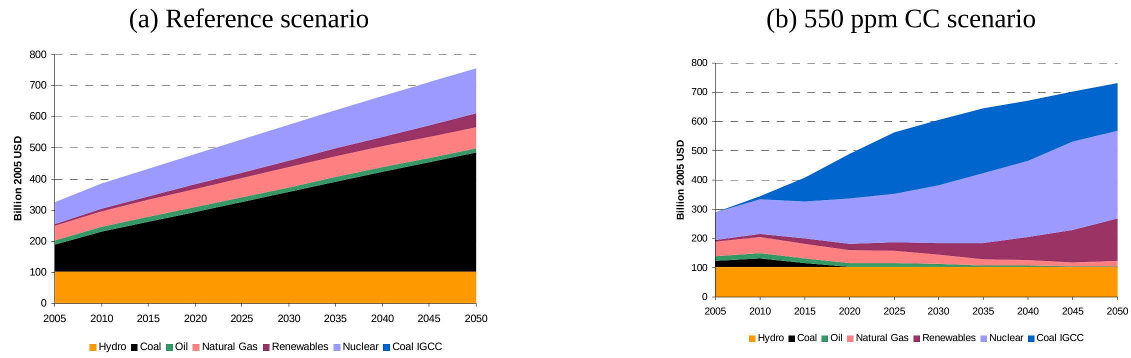



**Figure 2: Total investment in the power sector 2005-2050, by production technology.**

If we consider the time pattern of investments, our data suggest that the mitigation policy requires additional investments only for a quarter of a century, from 2020 until 2045; after 2045, the optimal level of investments in the *550 ppm CC* scenario converges to the one of the Reference scenario (Figure 1). A look at regional patterns shows that investments in OECD countries will be higher in the *550 ppm CC* scenario from 2015 until 2050, while Non OECD regions will reduce investments from 2010 to 2025 and also from 2040 until 2050. This different behavior is explained by higher space for energy efficiency improvements in Non OECD regions.

Total investments in the power sector do not increase in the *550 ppm CC* scenario with respect to the Reference scenario, but the decarbonisation of energy supply asks for a completely new energy mix and hence a radical re-organization of the power sector. Conventional fossil fuels power plants are progressively substituted by nuclear, coal power plants with CCS and renewables (Figure 2).

The *550 ppm CC* scenario requires a rapid reallocation of investments in power generation technologies. By 2020 it is optimal to stop investing in traditional coal power plants: coal can be used only if power plants are equipped with CCS. Nuclear becomes attractive in a carbon-constrained world. Soon after climate policy starts, the share of investments in these two technologies increases and becomes dominant from 2020 onward. Natural gas remains competitive in the first years of climate policy, but then gradually disappears. Only oil-rich regions continue to invest in oil power plants, although less than in the Reference scenario. Investments in renewable power generation – such as photovoltaic and wind – increase progressively and tend to replace investments in coal with CCS by the middle of the century. Hydroelectric power capacity is assumed to be already fully exploited and follows an exogenous dynamic in the model.

The joint analysis of Figure 1 and Figure 2 suggests that this quick reallocation of investments can be described as a succession of jumps. Fast-growing investments in nuclear power explain the first jump by 2010. This is immediately followed by two shocks: the first due to the deployment of CCS technologies in 2010 in OECD countries and the second, with a lag of ten years, in Non OECD countries.

We increase the detail of our analysis by focussing on the investments in net power capacity additions, which exclude investments to replace obsolete power plants. The lower panel of Figure 3 shows that climate policy reduces the expansion of the power sector. It is interesting to examine the diverging pattern of investments and new capacity additions between 2020 and 2030: while the expansion of power capacity declines of about 800 GW (which is equivalent to about 800 average-sized coal or nuclear power plants), the amount of investments increases. The average cost of power plants is thus increasing due to the penetration of nuclear, renewables and coal with CCS. These three technologies will basically cover all new capacity additions in a climate policy scenario because at 2050 electricity must be generated with almost zero carbon emissions.

The rapid shift towards a new mix of electricity generation technologies will be the real challenge of climate policy for the power sector. These three technologies have serious drawbacks. Nuclear has controversial implications and might not be accepted by the public opinion. As for coal power plants with CCS, it is still unclear if, and when, it will be possible to operate on a large scale. Finally, renewables have limitations due to low efficiency and grid connectivity problems.

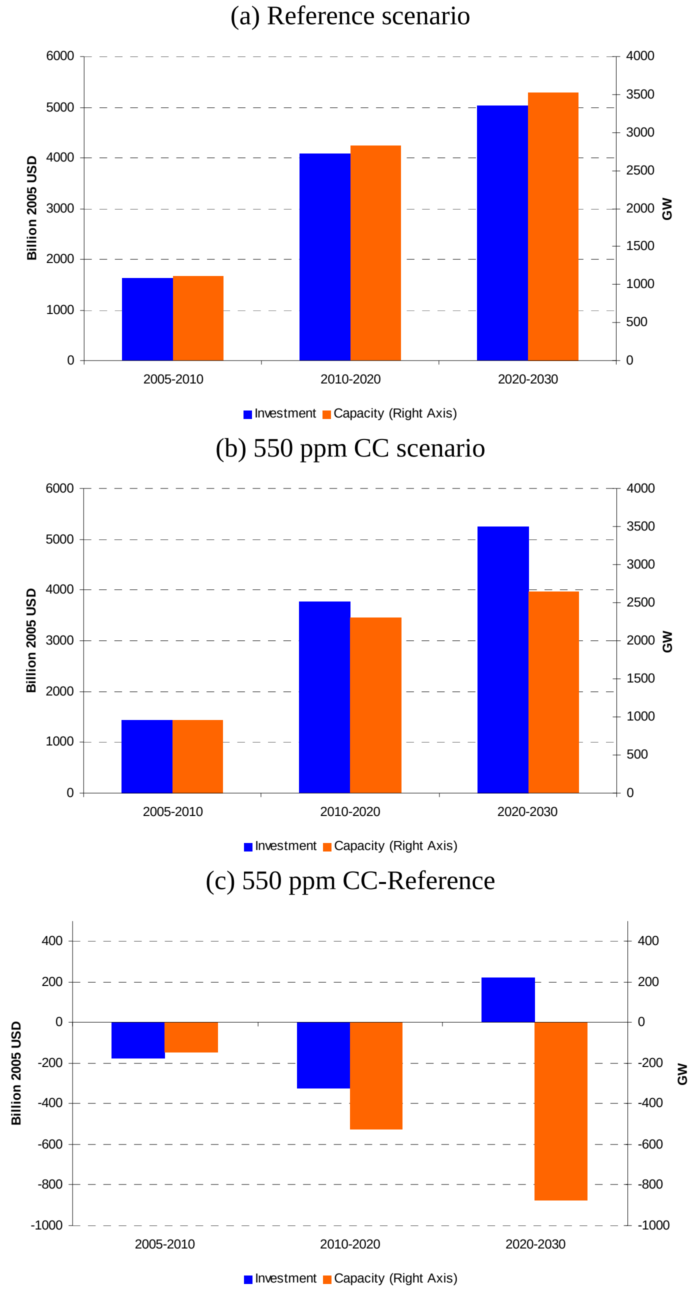



**Figure 3 World capacity additions and investment in power generation 2005-2030**

Even if financially manageable, the transition to a zero-carbon power sector will thus undoubtedly be problematic. In order to grasp the magnitude of the change, we propose a thought experiment in which power capacity can be expanded using either nuclear, hydroelectric or wind power plants. In the initial period 2005-2030, it would be necessary to install each year either 20 nuclear plants (of 1,000 MW each), or 33 large hydro plants (of 1,000 MW each), or 18,490 wind turbines (of 3 MW each). If we extend the time horizon further in the future, until 2050, the requirement becomes impressive: in order to meet the extra capacity 75 nuclear plants, or 126 hydro plants, or 70,213 wind turbines, have to be installed each year (Figure 4). To make these figures even more real we provide some examples. In December 2009 there were 436 nuclear power plants in operation for a total net installed capacity of 370,000 MW. The Three Gorges Dam will reach, when at full operation in 2011, 18,200 MW. In 2008 there was an estimated wind installed power capacity of 121,188 MW, which is equivalent to 40,396 3MW turbines.[17]

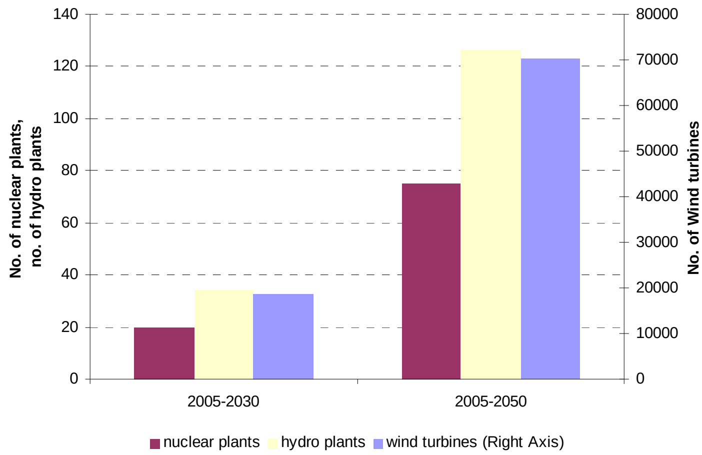



**Figure 4 Average number of new installations needed each year**

Investments are expected to shift across time, to move from fossil fuels based technologies to low- or zero-carbon power plants and also across regions.

Independently of the time span considered, the share of energy investments by Non OECD countries is lower in the *550 ppm CC* scenario than in the Reference scenario and is bigger than the share of OECD countries (see Table 5).

Looking more closely at the regional distribution of cumulative investments in the power sector it appears that the USA and the EU will sustain the long run investment cost of mitigation; in fact, the cumulative investment differential is negative for other countries (Figure 5). This effort is big, but affordable; for instance, the additional cumulative investment faced by the USA to tackle climate change would amount to USD 355.3 billion in 2050, an average yearly expense of USD 7.9 billion. This effort is comparable with the one US faced for one of the biggest infrastructure in the country, the Interstate Highway System, whose construction took 35 years (46,876 miles), representing an investment of USD 425 billion,[18] or an average annual investment of USD 12.1 billion.

In conclusion a low-carbon world does not necessarily require higher investments, but rather a totally new mix of investments. This means that stresses will not come from funding problems, bur the main challenge will be to govern the reallocation of investment across different industries with the complex distributional consequences involved in the process. Also, criticalities will emerge when large investments have to be diverted – in a relatively short time frame – from well-known technologies to ones that have associated higher technological risks. If risks and distributional issues will be managed appropriately, the amount of resources to be mobilized is not of an unprecedented size.

[17] Data are from the International Atomic Energy Agency (IAEA), the International Hydropower Association and the World Wind Energy Association.
[18] Figure expressed in 2006 USD. Source: Al Neuharth (2006-06-23), "Traveling Interstates is our Sixth Freedom," USA TODAY.

**Table 5 Cumulative investment in the power sector by region 2005-2050 (Billion 2005 USD)**

**(a) Reference scenario**

| | 2005-2010 | 2010-2020 | 2020-2030 | 2030-2040 | 2040-2050 | Total 2005-2030 | Share of total 2005-2030 (%) | Total 2030-2050 | Share of total 2030-2050 (%) | Total 2005-2050 | Share of total 2005-2050 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total OECD** | **886** | **2060** | **2342** | **2606** | **2851** | **5288** | **49.3** | **5457** | **42.5** | **10746** | **45.6** |
| **Total Non OECD** | **734** | **2024** | **2689** | **3367** | **4031** | **5447** | **50.7** | **7398** | **57.5** | **12845** | **54.4** |
| **Total World** | **1620** | **4084** | **5031** | **5973** | **6882** | **10735** | **100** | **12855** | **100** | **23590** | **100** |
| **Annual Average** | **324** | **408** | **503** | **597** | **688** | **429** | | **643** | | **524** | |

**(b) 550 ppm CC scenario**

| | 2005-2010 | 2010-2020 | 2020-2030 | 2030-2040 | 2040-2050 | Total 2005-2030 | Share of total 2005-2030 (%) | Total 2030-2050 | Share of total 2030-2050 (%) | Total 2005-2050 | Share of total 2005-2050 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total OECD** | **763** | **2076** | **2631** | **2921** | **3071** | **5470** | **52.3** | **5992** | **45.7** | **11463** | **48.6** |
| **Total Non OECD** | **681** | **1686** | **2622** | **3323** | **3795** | **4989** | **47.7** | **7118** | **54.3** | **12107** | **51.4** |
| **Total World** | **1444** | **3762** | **5254** | **6244** | **6866** | **10460** | **100** | **13110** | **100** | **23570** | **100** |
| **Annual Average** | **289** | **376** | **525** | **624** | **687** | **418** | | **656** | | **524** | |

**(c) 550 ppm CC-Reference**

| | 2005-2010 | 2010-2020 | 2020-2030 | 2030-2040 | 2040-2050 | Total 2005-2030 | Total 2030-2050 | Total 2005-2050 |
|---|---|---|---|---|---|---|---|---|
| USA | -74 | 10 | 152 | 165 | 125 | 88.6 | 290.2 | 378.8 |
| EUROPE | -15 | 46 | 119 | 141 | 129 | 149.7 | 269.7 | 419.3 |
| Other OECD | -33 | -41 | 18 | 10 | -34 | -56.1 | -24.8 | -80.9 |
| **Total OECD** | **-123** | **15** | **290** | **315** | **220** | **182.1** | **535.1** | **717.3** |
| China | -21 | -188 | -32 | -7 | -145 | -240.2 | -151.5 | -391.7 |
| Transition Economies | -13 | -24 | 8 | 30 | -8 | -28.6 | 22.8 | -5.8 |
| Other Non OECD | -20 | -126 | -43 | -68 | -84 | -188.9 | -151.4 | -340.3 |
| **Total Non OECD** | **-53** | **-338** | **-67** | **-44** | **-236** | **-457.7** | **-280.1** | **-737.8** |
| **Total World** | **-176** | **-323** | **223** | **271** | **-16** | **-276** | **255** | **-21** |

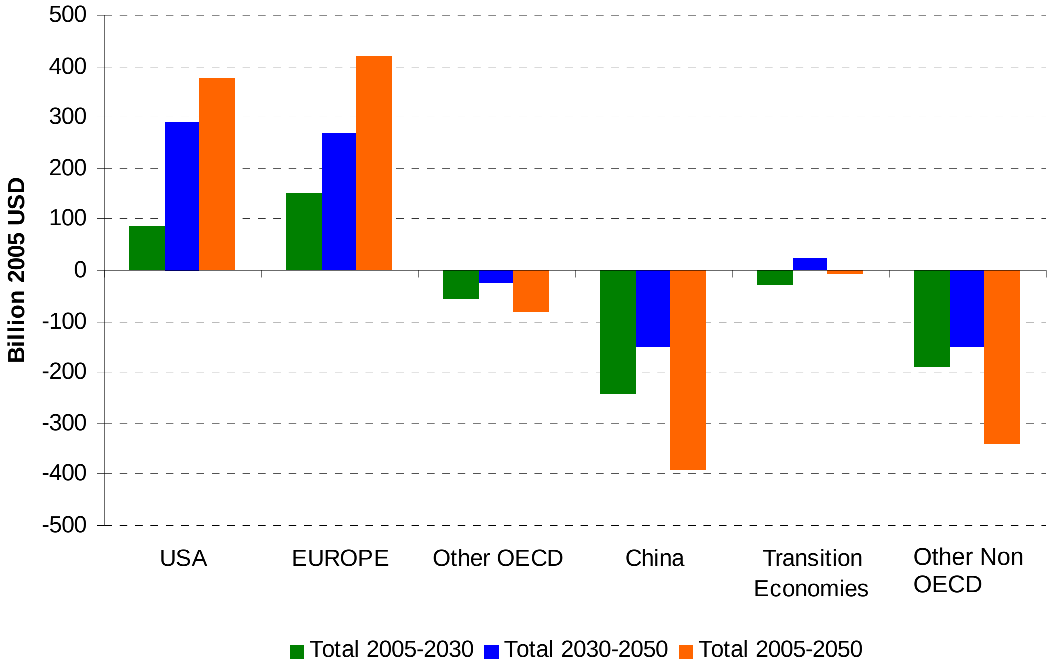



**Figure 5 Cumulative investment differential in the power sector by region, 2005-2050 (550 ppm CC-Reference)**

# 4. Financing Innovation

Radical transformations in the power sector and in the energy sector in general will be necessary but not sufficient to achieve a low-carbon world. They must be necessarily complemented by economy-wide large energy efficiency improvements to achieve the drastic reductions of emissions implied by low stabilization targets. Actually, since decarbonization measures are typically expensive, there is a wide agreement on the fact that energy efficiency must be the first area of intervention and will probably remain the most important for several decades. The scenarios produced by the WITCH model show that in 2020 it would be optimal to increase energy efficiency by 31 per cent while the carbon content of energy would decrease by only 5 per cent. This pattern will continue for decades and in 2050 the cumulated optimal improvement of energy efficiency is 70 per cent while the optimal contraction of the carbon content of energy is only 45 per cent (see Table 2).

Energy efficiency improvements can be achieved in WITCH by changing the optimal mix of capital, labor and energy services – the three major inputs in the aggregate production function of the model – and by investing in a stock of knowledge that increases the amount of energy services delivered by each unit of energy used. While the first mechanism describes process innovations in production and consumption, the second mechanism describes improvements in end-use equipment. Investments in R&D to increase the productivity of energy are thus needed in first instance to stimulate technological innovation in end-use energy technologies.

The decarbonization of the energy sector will be the result of the penetration of power generation technologies with low- or zero-carbon emissions and it will follow a gradual decarbonization of final energy consumption, in particular energy used for transport and for heating. In WITCH a representative carbon-free fuel and a representative carbon-free, large scale, electricity generation technology, become available if sufficient investments in R&D are made. The higher is the investment in R&D, the lower is the cost of this *backstop* technologies and the faster the substitution of natural gas, oil and coal in final consumption, and of fossil fuels based electricity generation in the power sector.[19] Thus, R&D contributes both to increase energy efficiency and to de-carbonize energy in WITCH.

A rich description of technological dynamics allows to produce more accurate scenarios of investments. In particular, models without endogenous technical change would overestimate the incremental investment over a Reference scenario. In order to appreciate this point, we produce an hypothetical scenario (550 ppm R&D fixed) in which R&D investments are fixed to the level they have in the Reference scenario. With reduced opportunities to increase energy efficiency and to decarbonize final energy consumption, the international carbon price will be higher and climate policy will be more costly (Figure 6 and Figure 7). Higher electricity demand requires higher installed capacity in the power sector, especially in more expensive power plants with low- or zero-carbon emissions, due to the limited possibilities of decarbonizing final energy uses. As a consequence, the percentage of investments directed to the energy sector is higher when R&D investments are forced to remain the same as in the Reference scenario (Figure 8).

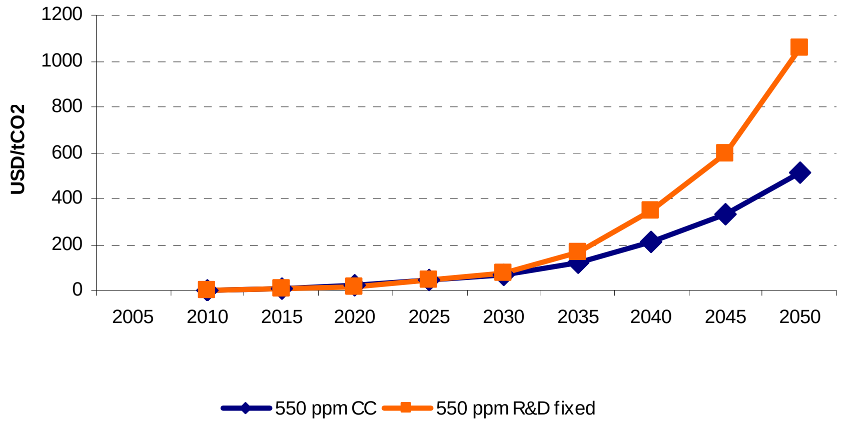



**Figure 6. Price of Carbon 2005-2050**

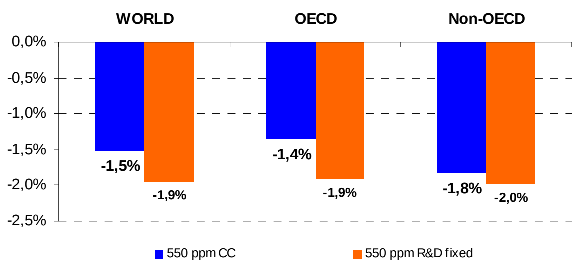



**Figure 7. Discounted Stabilization Policy Costs (3% declining): 2005-2050**

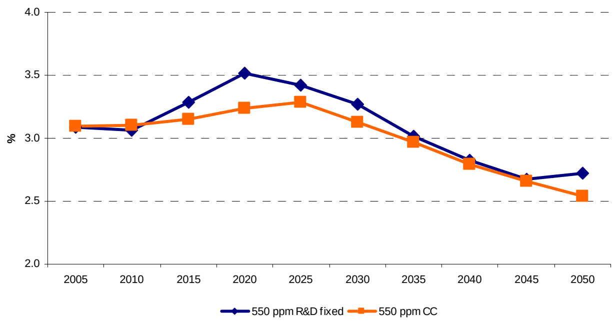



**Figure 8. Investment in the Energy Sector as % of Total Investment**

Figure 9 displays the time path of global R&D investments in the three knowledge stocks as a fraction of gross world product (GWP) and in absolute level for three different scenarios. If we compare the standard unconstrained *550 ppm CC* scenario, with the Reference scenario, we see that the model finds optimal to scale-up energy-related R&D investments five-fold, from the very beginning of climate policy.

[19] Investments in R&D are endogenous and augment three independent knowledge stocks. International energy R&D spillovers link regional technological advances. The cost of the backstop fuel follows a two-factors learning curve (Bosetti et al, 2009d). The cost of wind and solar power plants follows a one-factor learning curve with lagged international spillovers.

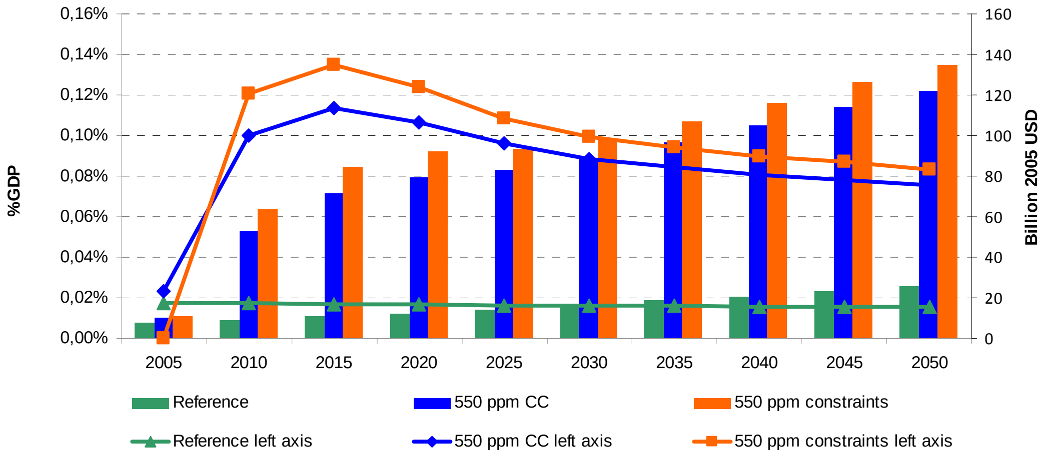



**Figure 9 Total R&D investment under different scenarios**

The increase of R&D spending is massive and prolonged until 2050; in relative terms, there is a spike in the first decades and then we register a stable pattern of R&D spending over GWP. The spike in R&D spending in the first years is explained by the sudden massive investment in research to develop the backstop fuel (Table 6).

The amount of R&D spending is a function of the technological scenario that we use. In a Constrained Policy scenario (550 ppm constraints), in which nuclear electricity is bound to current generation levels (*e.g.* for safety or political reasons) and the penetration of renewable power generation is limited to at most 25 per cent of total electricity supply (*e.g.* for distribution, transmission and intermittency problems), R&D investments increase with respect to the 550 ppm CC scenario (see again Figure 9). With constraints to nuclear and renewables, it is in fact optimal to invest in R&D to develop a carbon-free *backstop* power generation technology capable of operating on a large scale (see Table 6).

**Table 6 R&D Investment (Billion 2005 USD)**

| | | **No limit** | | | **Limit on nuclear and renewables** | | |
|---|---|---|---|---|---|---|---|
| | | Additional energy efficiency | R&D Back NEL | R&D Back EL | Additional energy efficiency | R&D Back NEL | R&D Back EL |
| **OECD** | 2020 | 6.22 | 33.49 | -- | 7.09 | 33.26 | 7.08 |
| | 2030 | 11.05 | 29.65 | -- | 12.23 | 29.27 | 5.57 |
| | 2050 | 23.73 | 28.44 | -- | 25.67 | 28.05 | 5.59 |
| **Non OECD** | 2020 | 1.70 | 25.61 | -- | 1.84 | 25.54 | 4.86 |
| | 2030 | 3.70 | 27.85 | -- | 3.97 | 27.55 | 4.00 |
| | 2050 | 10.59 | 33.35 | -- | 11.33 | 33.00 | 5.02 |
| **World** | 2020 | 7.91 | 59.08 | -- | 8.93 | 58.80 | 11.93 |
| | 2030 | 14.76 | 57.50 | -- | 16.20 | 56.82 | 9.56 |
| | 2050 | 34.31 | 61.79 | -- | 37.01 | 61.06 | 10.61 |

Our scenarios have useful insights for policy makers. They show that despite the financial flows needed to boost R&D activities are modest from a macroeconomic perspective (at most 0.14 per cent of GWP), the fast expansion of R&D spending represents a formidable challenge from a managerial perspective. Our economies will be perfectly able to finance the expansion in energy related R&D expenditure. A real threat comes instead from the impressive effort needed to mobilize these financial resources in a short time. We must also consider that governments' support will probably be necessary to fund research in *backstop* technologies for three reasons. First, private investors might not be willing to undertake the high risks of frontier research. Second, knowledge market externalities are a well-known problem that is particularly acute for the basic research activity needed to develop breakthrough technologies. Finally, especially for a *backstop* power generation technology, large scale projects will be costly and will require the partnership of many governments (i.e. the large scale collider at CERN cost Euro 3 billion and it involved 20 member states and six observer nations[20]).

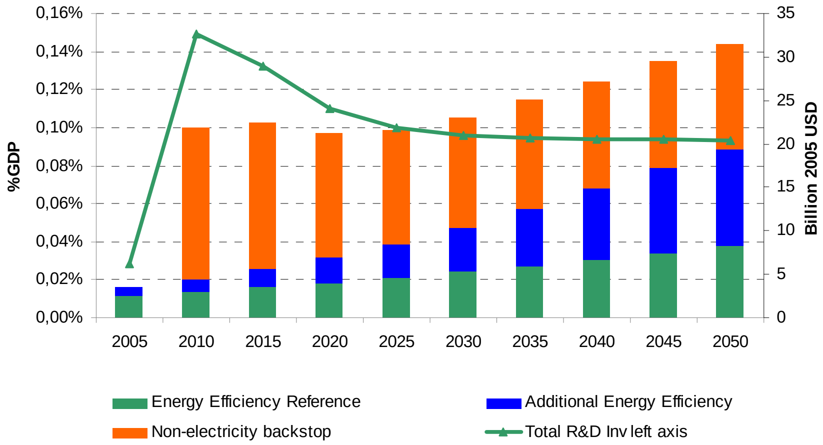



**Figure 10 USA Total R&D investment**

With a strong political commitment there are chances however that these difficulties can be overcome. In fact, in the past, vast amounts of resources have already been successfully mobilized to finance ambitious technological advancements in a short time frame. For example, in the 1960s the Apollo Space Programme of the NASA has required a massive investment that is comparable to what would be necessary to spend to develop a *backstop* fuel in the United States (Figure 10). To send a man on the moon the NASA spent approximately 97.9 billion of USD, at 2008 prices, over 13 years, which reaches the 0.4 per cent of the average national GDP during the peak year of funding (Stine, 2009). In GDP terms this is much less than what is required in our R&D investment scenario for the USA.

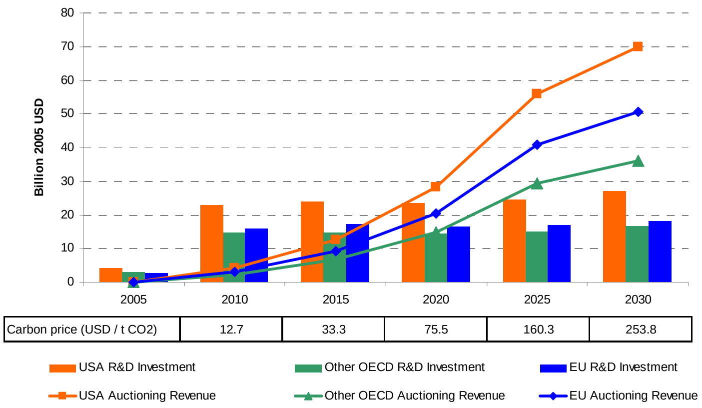



**Figure 11 Stabilization Scenario: Auctioning revenue (20% auctioned) and R&D investments**

Revenues from auctioning carbon allowances – or fiscal revenues from carbon taxes – can be a major source of income for R&D investments. This is a widely discussed idea that we can test using the scenarios for R&D expenditures and the price of carbon allowances that clears the international carbon market in WITCH. We start by assuming that 20 percent of carbon allowances are auctioned in all regions. The growing price of carbon quickly generates a flow of income sufficient to cover all R&D investments in advanced economies starting from 2020 (Figure 11). After 2020 the revenues from auctioning will largely exceed the demand of funds to cover energy related R&D. Most interestingly, we can compute the exact share of permits that is necessary to auction to cover investments in R&D in the USA, in Europe and in other OECD economies.

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[20] http://askanexpert.web.cern.ch/AskAnExpert/en/Accelerators/LHCgeneral-en.html#3 and http://www.lhc.ac.uk/about-the-lhc/faqs.html viewed on November 30th 2009.

Initially, the low-carbon price and the high spending in R&D require about three quarters of permits to be auctioned for this purpose. This share declines quickly to a modest 5 per cent in 2030, as shown by Table 7, for all three regions, mainly because the carbon price will increase substantially after 2020. To put these figures in perspective for the USA, the 22 billion from auctioning permits are roughly equivalent to 5 per cent of the total 2007 USA corporate tax revenue.[21]

This simple exercise yields an interesting policy insight. Revenues from auctioning carbon allowances or from carbon taxes should initially be devoted almost exclusively to finance R&D. There are other noteworthy options for recycling carbon revenues – for example lump-sum transfers to low income households would reduce the regressive component of carbon pricing – but a dispersed re-distribution of carbon revenues would miss the opportunity to create a large R&D fund that has the chance of financing the breakthroughs towards a low-carbon world.

**Table 7 Weighing auctioned revenue and R&D investments**

| | **OECD** | | **USA** | | **Europe** | |
|---|---|---|---|---|---|---|
| Years | % of permits auctioned | R&D investments = auctioning revenue (Billion 2005 USD) | % of permits auctioned | R&D investments = auctioning revenue (Billion 2005 USD) | % of permits auctioned | R&D investments = auctioning revenue (Billion 2005 USD) |
| **2010** | 76% | 48.128 | 71% | 21.906 | 75% | 15.296 |
| **2015** | 28% | 51.151 | 27% | 22.453 | 27% | 15.494 |
| **2020** | 14% | 49.917 | 13% | 21.278 | 13% | 15.380 |
| **2025** | 9% | 50.634 | 8% | 21.541 | 8% | 15.540 |
| **2030** | 5% | 53.686 | 5% | 23.005 | 5% | 16.270 |

## 5. The Carbon Market: from "Fossil Finance" to "Carbon Finance"

If a successful, stringent, long-term mitigation policy will be implemented, the twenty-first century will see the emergence of a new key commodity, carbon, whose value will increase considerably over time. At the same time, this century will witness and an historic decline of oil, natural gas and coal markets, three major international commodities for centuries. In particular, the oil market will likely evanish during the century, long before oil is exhausted, because its consumption is more dispersed than coal and natural gas and there is no technology to capture and store carbon from diffused emissions. All models unanimously confirm this scenario. The question is rather when and at what pace the oil market will start to disappear.

This section is devoted to a comparative analysis of the dynamics of financial flows associated to carbon – "carbon finance" – and of financial flows associated to fossil fuels – "fossil finance" – during the transition towards a low-carbon world.

According to our Policy scenario, an hypothetical world carbon market will be larger than the future oil market by a factor of six by the middle of the century, with the take-over happening between 2035 to 2040. This rough estimate is obtained considering the primary markets alone. Financial transactions connected to carbon trade will grow in value for the combined effect of larger exchange of carbon permits and growing carbon prices.[22] Assuming that the share of oil traded internationally is fifty percent, the financial flows associated to oil transactions will decline for a contraction of demand and for lower oil prices. Keeping carbon in the ground will in fact be a more profitable business than extracting fossil fuels. Even in the case of fragmented carbon markets – or if the policy tool will be a carbon tax – the value of carbon will be higher than the value oil and other fossil fuels (Figure 12).

[21] Bureau of Economic Analysis: Government Current Receipts and Expenditures http://www.bea.gov/national/nipaweb/GovView.asp. view on October 2009.
[22] Our estimate, based on the standard Policy scenario in which carbon allowances are distributed according to the "contraction and convergence" rule, is obtained by simply multiplying the value of carbon by the quantity traded internationally.

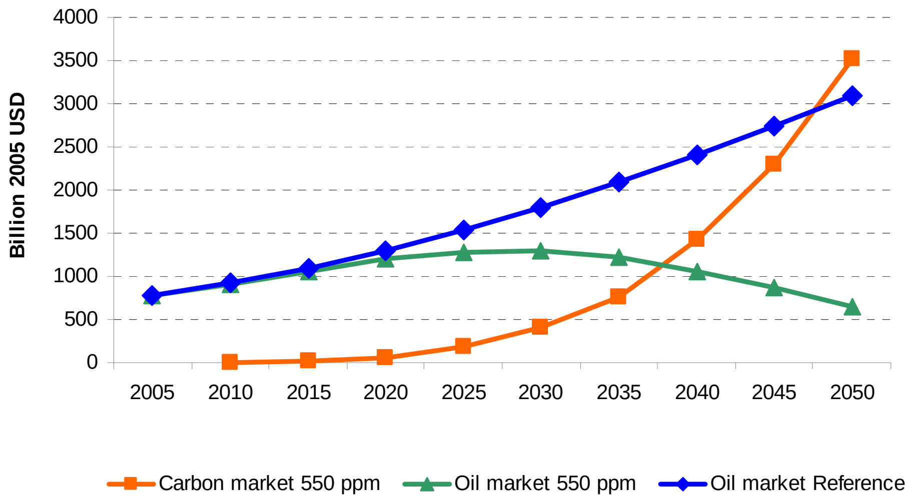



**Figure 12 Oil and carbon market value in 550 ppm CO2e scenario**

The size of an hypothetical future world carbon market will depend on the international distribution of carbon allowances: the greater will be the unbalance between the level of emissions and the endowment of permits, the greater will be the incentive to use international offsets to achieve the domestic targets. The value of carbon will change instead only marginally with different allocation rules, being it primarily a function of both the severity of the stabilization target and technological progress. The degree of openness of the international carbon market, by influencing the efficiency of global abatement, will also have an impact on carbon prices.

We explore these issues using a set of Policy scenarios developed by the WITCH model with different emissions permits allocation rules and a variety assumptions on the degree of openness of the international carbon market.

The *550 ppm CC* Policy scenario used the “contraction-and-convergence” rule to distribute emissions permits internationally. A second possibility would be to distribute emissions permits in proportion to population right from the beginning of climate policy, without the adjustment period which characterizes the “contraction-and-convergence” rule. This second scheme is referred to in the literature as the “equal-per-capita” (EPC) distribution rule and we use it in the 550 ppm EPC scenario.

We explore the implications of limiting international carbon offsets using the contraction-and-convergence rule. While in the standard Policy scenario (*550 ppm CC*) regions have free access to the international carbon market, we developed three scenarios – *550 ppm CC 25 %, 550 ppm CC 50%, 550 ppm CC 75%* –in which we limit the purchase of international offsets to 25 per cent, 50 per cent and 75 per cent of the national abatement target.

Although informative, scenarios with limited access to international carbon market have little chances of being implemented because they would raise domestic abatement costs. For example, the European ETS II-III phases (2008-2020) and the recently proposed USA Waxman-Markey bill, have both very lax constraints: the European Union will limit international carbon offsets to 1.6-1.7 billion tons of $CO_2$ in the period 2008-2020, while the Waxman-Markey bill limits international offsets to one billion tons of $CO_2$ annually, with an extra billion ton of domestic offsets.[23] Not surprisingly, both constraints are not binding until 2025 according to our Policy scenarios. If we look at Figure 13, we see that in case of unlimited access to international carbon markets Europe will make one billion tons of $CO_2$ international offsets, largely below the limit

[23] http://ec.europa.eu/energy/climate_actions/doc/2008_res_ia_en.pdf and http://energycommerce.house.gov/Press_111/20090724/hr2454_housesummary.pdf view on November 2009

imposed by the current legislation. With different assumptions on openness of international carbon markets, the use of offsets might increase, not exceeding however the limit of 1.7 cumulative billion tons. For the USA, the Waxman-Markey limit of one billion tons of $CO_2$ per year will become stringent only after 2025, as shown in Figure 14.

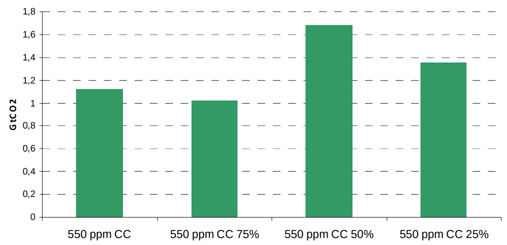



**Figure 13 Cumulative international offsets, Europe (2010-2020)**

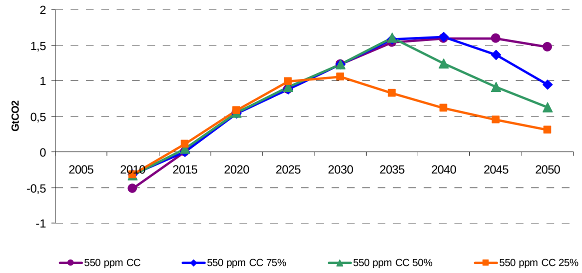



**Figure 14 International offsets, USA**

With both allocation rules (*550 ppm CC* and *550 ppm EPC*) and unlimited access to international offsets, the value of the carbon market will increase exponentially over the time, reaching more than USD 3.5 trillion in 2050, when the two allocation rules converge (Figure 15). With limited access to international offsets the value of carbon markets will be smaller because of the combined effect of reduced trading volume and lower carbon value. Only in the *550 ppm CC 25%* scenario the value of the carbon market stops increasing after 2030.

The most important factor influencing the size of the international carbon market is the allocation rule used to distribute emissions permits. While in the equal-per-capita allocation rule the largest fraction of global emission permits is distributed to low income-high population regions, with very low per capita emissions and thus low abatement targets, in the contraction-and-convergence rule, permits tend to be distributed, especially in the first decades, where emissions are, thus limiting the need to use international offsets. Therefore, it is not surprising that the 550 ppm EPC scenario displays a much higher volume of international carbon offsets, as shown in Figure 16. The limits to the access to international offsets become binding after 2030, with only the *550 ppm CC 25%* scenario departing significantly from the unrestricted *550 ppm CC* benchmark.

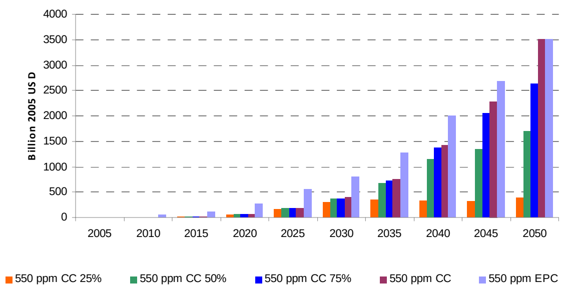



**Figure 15 Carbon market value**

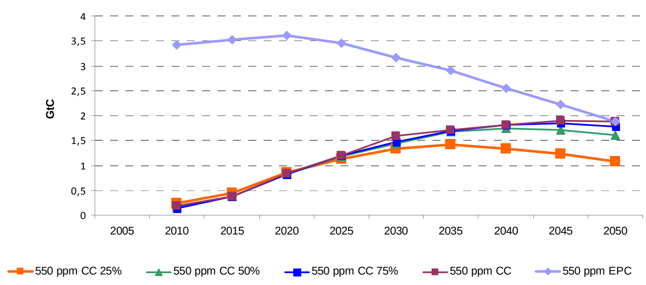



**Figure 16 Carbon market volume**

With limits to international offsets marginal abatement costs are not equated globally. With competitive markets, the greater is the restriction to trade, the lower is size of the market and the price of carbon, as shown by Figure 17. This happens because when offsets are bounded, only the cheapest abatement opportunities are financed, leaving unexploited the most expensive. Accordingly, with limited international offsets the price of carbon becomes an imperfect signal of the severity of climate policy: although the price of carbon is lower with limited access to international offsets, climate policy costs increase, as detailed in Figure 18.

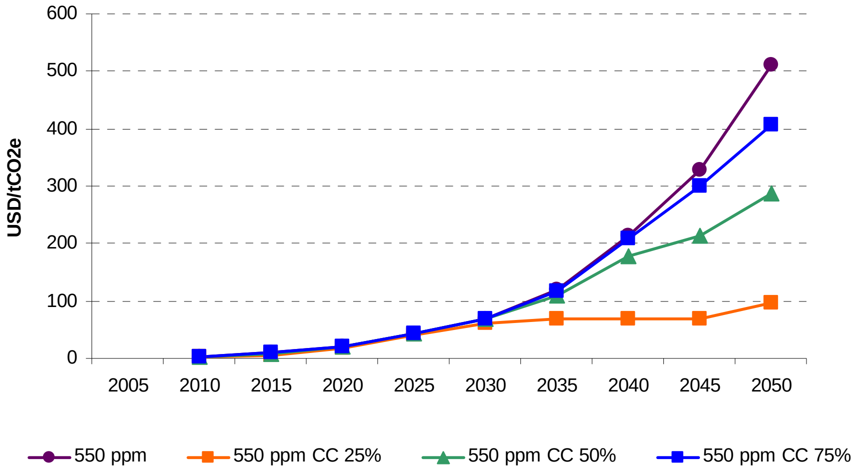



**Figure 17 Price of Carbon under different limit to International offsets**

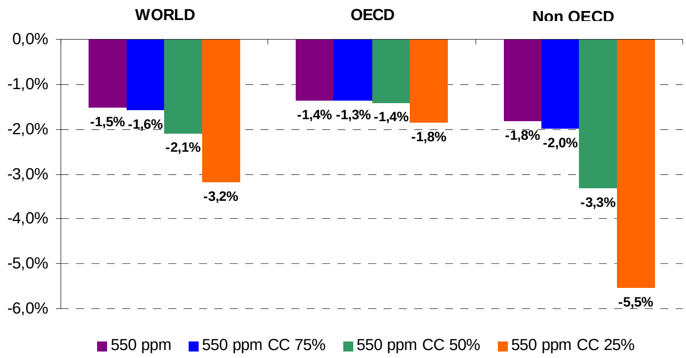


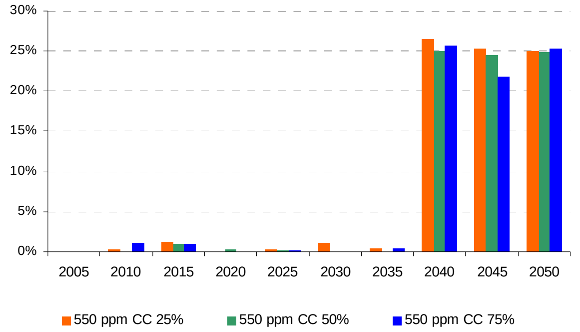

**Figure 18 Discounted Stabilization Policy Costs (3% declining) (2005-2050)**

Constraints to international carbon offsets reduce the overall efficiency of climate policy and increase costs for all regions. Costs in Non OECD countries are more sensitive to assumptions on the openness of carbon markets than costs in OECD countries. This is explained by the loss of large financial inflows from carbon offsets in some developing regions, especially in South Asia (SASIA) – which includes India – and in Sub-Saharan Africa (SSA), both with low emissions and large population.

When limits on international carbon offsets are stringent, regions with a deficit of carbon permits will have higher marginal abatement costs because a larger fraction of abatement is domestic. Indeed, for these regions, the domestic shadow price of carbon will be higher than the international one (the reverse will be true for countries with an abundant allocation of permits). An interesting implication is that investments to decarbonize the energy sector will increase, as depicted in Figure 19 for the USA and Europe. When the limit on international carbon offsets becomes stringent, optimal investments in the energy sector increase roughly by 25 per cent in Europe and between 25 per cent and 30 per cent in the USA, with respect to the Policy scenario without constraints (*550 ppm CC*). Hence, the carbon market could act as a tangible indirect source of investments in the energy sector.

A crucial question is if the financial flows associated to the international carbon offsets are sustainable from a political and an international macroeconomic point of view. Notes:
CAJANZ (Canada, Japan, New Zealand); USA; LACA (Latin America, Mexico and Caribbean); WEURO (Western Europe); EEURO (Estern Europe); MENA (Middle East and North Africa); SSA (Sub-Saharan Africa excl. South Africa); TE (Transition Economies); SASIA (South Asia); CHINA (including Taiwan); EASIA (South East Asia); KOSAU (Korea, South Africa, Australia) displays a regional breakdown of financial flows associated to carbon trading under different degrees of openness of the carbon market.

(a) Europe




(b) USA

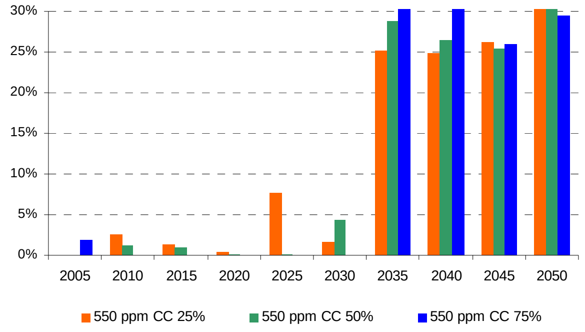
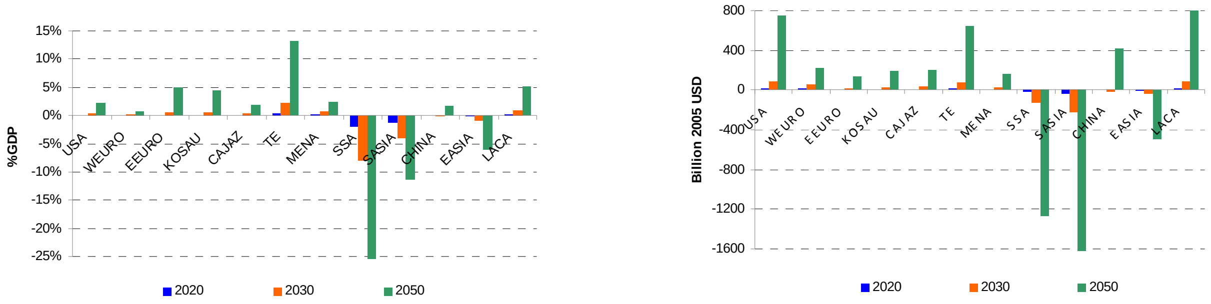


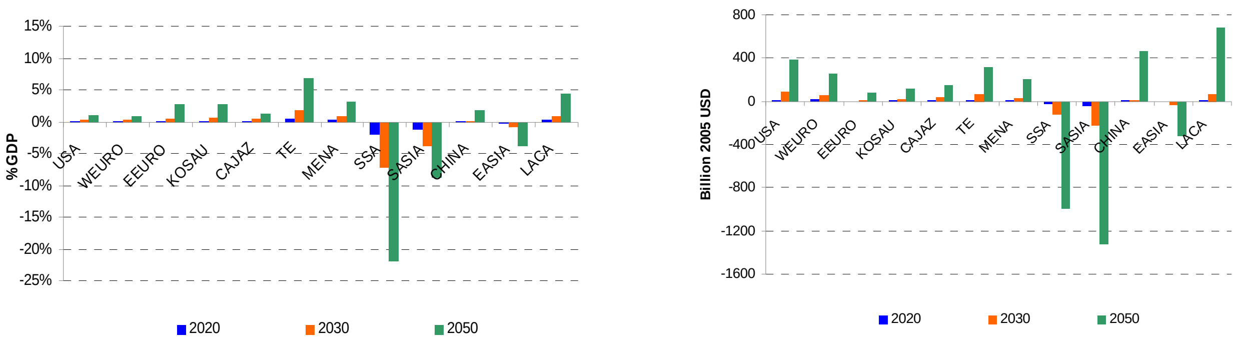

**Figure 19 Change in Energy Investment when International Offsets are Limited**

With unrestricted access to international offsets Sub-Saharan Africa (SSA) and South Asia (SASIA) are the two large suppliers of cheap abatement options; with growing carbon prices the financial inflow in these two regions would be 25 per cent and 11 per cent of annual regional GDP in 2050. Especially for Sub-Saharan Africa, selling carbon permits would become the major economic activity. In 2020, when the carbon price is still very low and the demand of permits from developed regions is low in the realm of a contraction-and-convergence rule, the transfer to Sub-Saharan Africa would be around USD 18 billion in all scenarios. In order to put these figures in perspective, we should consider that in 2007 the net Official Development Assistance (ODA) to Africa amounted to USD 38.7 (DID, 2009) and thus carbon trade would become a primary source of revenues for low income countries.

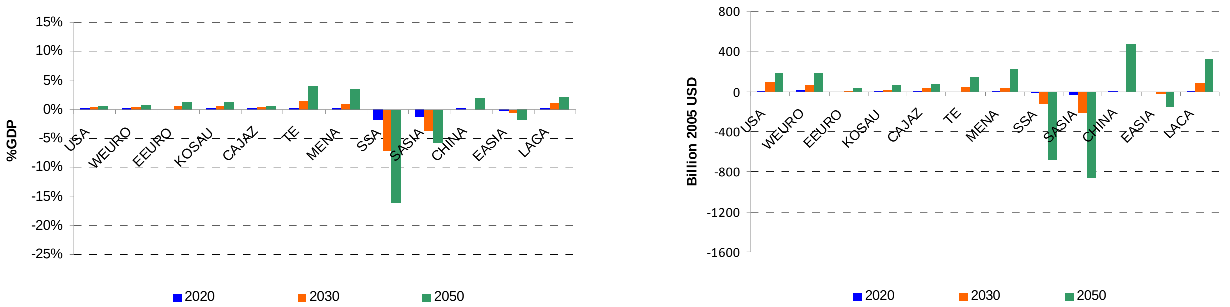
However, huge financial flows would disrupt the balance of payments of low income regions and cause other serious macroeconomic disruptions (McKibbin and Wilcoxen, 2006). From a political standpoint, it is hard to imagine that extremely large financial flows will be accepted by high income countries. It is thus perfectly reasonable to expect a limit to international carbon offsets in the future, when carbon price becomes to increase sharply. A threshold of about 25 per cent is a realistic option from a financial perspective but it leads to a doubling of mitigation policy costs (Figure 18). A looser target might then be preferable and a wider access to carbon finance can be compensated with correction measures to avoid large financial transfers to developing countries.



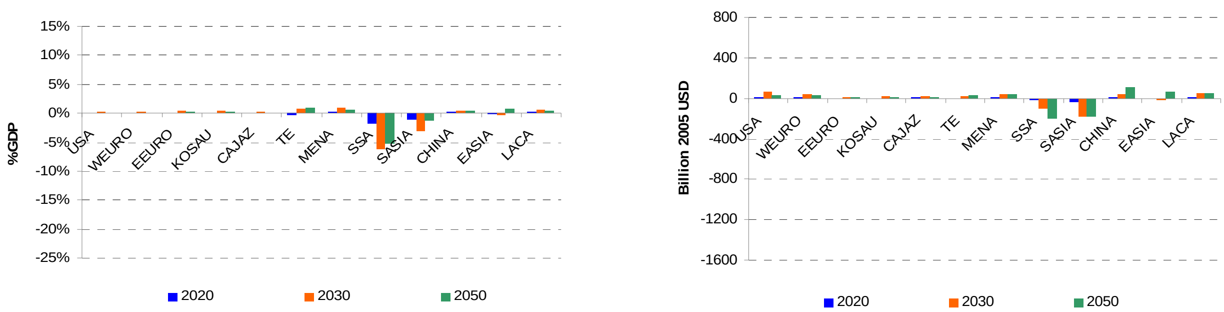

(a) 550 ppm CC




(b) 550 ppm CC 75%




(c) 550 ppm CC 50%




(d) 550 ppm CC 25%

**Figure 20. Trading value in absolute and as % of GDP**

**Notes:**
CAJANZ (Canada, Japan, New Zealand); USA; LACA (Latin America, Mexico and Caribbean); WEURO (Western Europe); EEURO (Estern Europe); MENA (Middle East and North Africa); SSA (Sub-Saharan Africa excl. South Africa); TE (Transition Economies); SASIA (South Asia); CHINA (including Taiwan); EASIA (South East Asia); KOSAU (Korea, South Africa, Australia)

## Conclusions

In study we have investigated investments and financial flows induced by mitigation policy aimed at stabilizing GHG concentration at 550 ppm $CO_2$-eq at the end of the present century. In particular, we explore what are implications of the stabilization policy for investments in the power generation sector, the financial requirements to foster R&D activities and the dynamics of carbon markets

We find that climate policy will not induce higher investments in electric power generation with respect to the Reference scenario. It is true that zero- or low- carbon emitting power generation technologies are more expensive than traditional coal and natural gas power plants, but it must also be acknowledged that in many cases it will be cheaper to reduce electricity demand than invest in these expensive technologies. In fact, we find that higher average investment costs in electricity generation are totally offset by a contraction of electricity demand. Thus, a low-carbon world does not require higher investments but rather to shift resources towards a totally new technological mix. Criticalities will emerge when large investments have to be diverted – in a relatively short time frame – towards intrinsically complex and risky technologies. However, if these risks will be managed appropriately the amount of resources to be mobilized is not of an unprecedented size.

Similar issues emerge when we look at the financial requirements to sustain a technological revolution in the energy sector. A large number of scenarios produced using the WITCH model consistently show that it would be optimal to scale-up energy-related R&D expenditures from the very beginning of climate policy. R&D should be directed to increase energy efficiency and to develop and deploy zero emissions backstop technologies. This fast expansion of R&D spending represents a formidable challenge from a managerial perspective, but the overall financial requirements are minimal, summing up to a fraction of a percentage point of gross world product. Thus, from a pure financial perspective our economies will be perfectly able to finance this historical expansion in energy related R&D expenditure. The real threats come instead from the impressive managerial effort needed to mobilize such a large scale effort in a short time and from the well known failures in innovation markets. Governments will necessarily step in to support R&D, especially in large scale, very uncertain, projects. Public budgets problems can be eased using revenues from carbon taxes or from auctioning carbon allowances. The size of funds from carbon pricing will be large enough to finance R&D expenditure from the first years of climate policy.

If a successful, stringent, long-term, mitigation policy will be put into place, the twenty-first century will see the emergence of carbon finance and an historic decline of oil, natural gas and coal markets. As a pure reference scenario, we show that a hypothetic world carbon market will be larger than the future oil market by a factor of six by the middle of the century, with the take-over between 2035 and 2040. Moreover, in the case of fragmented or national carbon markets – or if the policy tool will be a carbon tax – the value associated to carbon will be higher than the value associated to oil and other fossil fuels: keeping carbon in the grounds will be a more profitable business than extracting fossil fuels.

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