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LIMITS

Low climate IMpact scenarios and the Implications of required Tight emission control Strategies

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DELIVERABLE No 2.3
Report focusing on the financing mechanisms required to raise and manage economic resources needed to limit the global temperature increase to 2°C

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DELIVERABLE NO. 2.3

Report focusing on the financing mechanisms required to raise and manage economic resources needed to limit the global temperature increase to 2°C[1]

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1. Introduction

The question of how to finance the transition to a low-carbon society has been a popular research topic in recent years (FS-UNEP and BNEF 2013; UNCTAD 2010; UNFCCC 2007; WEF 2013). This popularity has been due to a variety of reasons (Campiglio 2013).

First, moving towards the creation of a sustainable economy is seen by many – scholars, governments and international institutions – as necessary and urgent (OECD 2011; Stern 2006; World Bank 2012). Although the transition to a green economy involves inter-related changes to large parts of the economy and is therefore systemic in nature, three developments will be central:

i. The production of energy from clean and renewable sources (for example, solar panels and wind turbines);
ii. The improvement of energy efficiency (especially in buildings and transport);
iii. The conservation and smart use of natural capital (by means of sustainable agriculture, fishing, water, waste, and other environmental services).

The expansion of these activities is likely to help reconcile short-term objectives – GDP growth, economic stability, employment – with long-term considerations regarding the impact of society on ecological resources (ILO 2012; UNEP 2011).

Second, in order for the transition to take place, substantial economic resources have to be used to create capital embodying low-carbon technologies. The level of additional investment is not known with certainty, but a range of estimates exists. For example, UNEP (2011) calculates that the yearly additional investment required to deliver a green economy would be on average around 2% of the global GDP over the 2010-50 period ($1 to $2.6 trillion). According to WEF (2013), the investment needed to respond adequately to the climate challenge is around $700 billion per year, from now until 2030. McCollum et al. (2014) use a number of Integrated Assessment Models to find that climate policies consistent with the 2°C ceiling on the increase in global temperature since pre-industrial times would entail additional investment in both energy supply and demand of about $800 billion. This order of magnitude is confirmed also by the survey by Olbrisch et al. (2011), who report several estimates of additional investment ranging from $400 billion per year to more than $1,200 billion per year.

Finally, despite the fact that such a surge in investment is far from unprecedented and less investment will be needed in fossil-fuel energy supply and distribution (Bowen et al. 2014), shifting the required resources to the low-carbon sectors is proving to be very challenging.

Investment in renewable energy[2] – especially solar and wind energy – has been growing at a fast pace in recent years, reaching approximately $244 billion in 2012, an amount five times larger than in 2004 (FS-UNEP and BNEF 2013). The expansion has been particularly robust in developing regions, with China currently the main investor in renewable energy at around $67 billion in 2012. However, despite some promising trends, the gap between current investment and the amount required to respect the 2°C limit remains wide, and no certainty exists about the means to fill it. Indeed, investment in clean energy is currently declining, as 2012 recorded a 12% drop from the previous year. The first two quarters of 2013 showed an even worse performance (BNEF 2013b), driven by widespread cuts in government support and pessimism about the general economic perspective.

In order to reverse this adverse development, and to stimulate the expansion of a sustainable economy, a larger proportion of the economic activity must be directed towards the sectors producing low-carbon goods, services and technologies. In other words, for the low-carbon transition to take place, economic agents must be both willing and able to increase their spending in these sectors. Firms have to carry out investment in new plant and equipment, hire workers and pay for intermediate goods; households must purchase the goods and services produced by green firms and pay for investment in their homes (e.g. home energy efficiency retrofit); and the government has to spend to build energy and transport infrastructure and finance clean-energy R&D. Both the private and the public sector are indispensable components of the low-carbon transition.

However, a variety of market failures – the most important of which is the exclusion of environmental goods from the pricing system – typically make it unattractive for the private sector to spend and invest in low-carbon sectors. For this reason, the first and foremost condition to be met for the incremental spending to take place is the introduction of a carbon price. More broadly, a comprehensive and well-calibrated set of prices taking into account environmental externalities should align the incentives facing households and firms with environmental objectives, so that agents *want* to facilitate the transition to an environmentally sustainable economy. The spread of environmental pricing also entails a central role for a well-designed public finance framework. As argued in section 3 below, public revenues from carbon taxation in particular are likely to be substantial, and ways of using these revenues must be discussed.

Nevertheless, although crucial for the transition to a green economy, a well-designed fiscal system with environmental pricing is not sufficient in itself to guarantee that low-carbon sectors flourish. An equally important factor is the availability of credit to potential investors. The years since the 2007 global financial crisis have shown how, under certain macroeconomic conditions, banks may not be willing to provide adequate funds to finance investment even though rates of return (with environmental pricing) superficially appear attractive. As argued in section 4, the

[2] Data cover investments in: solar, wind, biomass & waste, small hydro, biofuels, geothermal and marine. Large hydro schemes (>50 MW) are excluded.

market failure concerning credit creation and financial intermediation also calls for public intervention and the implementation of more effective policies, just as with the market failure due to greenhouse gas externalities.

The analysis in this Report draws extensively on the results of the models used by participants in the LIMITS project – 'Low climate IMpact scenarios and the Implications of required Tight emission control Strategies' (Kriegler 2014; Tavoni 2014). A classification of LIMITS scenarios can be found in Table 1. In particular, this Report focuses on two of the seven models: the WITCH model (Bosetti et al. 2007) and the REMIND model (Leimbach et al. 2010), both of which have a general equilibrium structure that allows the more detailed analysis of some of the macroeconomic variables involved in climate-change policies, and in particular that allows incremental investment costs and aggregate costs to be distinguished[3].

The structure of the report is thus as follows. Section 2 analyses the macroeconomic framework of the LIMITS models and presents their results concerning growth, investment – both aggregate and energy-supply-related – and the macroeconomic costs of climate-change mitigation. Section 3 focuses on public finance, discussing the need for public intervention. The LIMITS models are employed to study the interaction between carbon tax revenues and energy-supply investment. Section 4 turns to private finance and analyses different ways through which credit can be channelled towards low-carbon activities. Finally, section 5 concludes.

[3] See also Michael Jakob et al., 'Description of the Recipe Models', *RECIPE Background Paper,* (2009).

2. A macroeconomic analysis of LIMITS results

Integrated Assessment Models (IAMs) have proved to be crucially important tools to analyse the dynamic interactions between the economic, energy and climate systems. During the past two decades, since the first models attempting to link climate with the economic system (Nordhaus 1993; Nordhaus and Yang 1996), research using Integrated Assessment Models has made large steps forward. A wide variety of different models are now routinely used to assess climate policies, as demonstrated by increasingly numerous comparative exercises (Calvin et al. 2012; Clarke et al. 2009; Luderer et al. 2012).

The evolution of IAMs has entailed the expansion and refinement of their energy and climate modules by the explicit representation of different sources of energy, greenhouse gases and technologies, the primary research objective being to identify the optimal future emissions trajectories and to understand how to shape energy systems in order to achieve them. Given the great complexity of modelling energy and climate, most IAM designers have preferred to keep the economic modules relatively simple, conforming to the neoclassical Ramsey-type growth theory based on the intertemporal optimization of consumption (Acemoglu 2009; Ramsey 1928). Some other IAM designers have decided to avoid the welfare problem and focus instead on the minimisation of energy system costs, or to create a 'soft link' between cost-minimizing energy system models and welfare-maximizing macro models[4] (Bauer et al. 2008). As a result, some of the wider macroeconomic implications of IAM simulations have yet to be properly explored and hence this section has two main objectives.

First, a more detailed analysis is carried out of some of the macroeconomic variables that are usually included in IAMs results but tend not to be considered when evaluating the economic implications of climate-change policies. The most common macroeconomic assessment of simulations in the literature concerns the *aggregate costs* of climate policies, calculated as the percentage loss of GDP or consumption with respect to business-as-usual scenarios. However, as argued by Carraro et al. (2012), there are other important pieces of economic information that can be extracted from simulations such as projected investment – in physical capital, energy capacity and R&D – and tax revenues. For this reason, in the following sections a wider set of variables is considered and compared with macroeconomic costs, and a brief discussion of how LIMITS results compare with historical data is offered.

However, the current state of the art of Integrated Assessment Modelling still does not allow a comprehensive analysis of the macroeconomic implications of climate-change policies. For this reason, this Report is not limited to the consideration of IAMs output. The distinction between

[4] For a more detailed classification of IAMs, see Elizabeth A. Stanton, Frank Ackerman, and Sivan Kartha, 'Inside the Integrated Assessment Models: Four Issues in Climate Economics', *Climate and Development,* 1/2 (2009), 166-84.

public and private finance, for example, is something that typically does not appear in IAMs but has important ramifications for the size and direction of investment flows. In section 4, the sources of credit for private finance and their implications for financing climate-change mitigation activities are considered, another aspect neglected by IAMs.

2.1 The macroeconomics of LIMITS models

The dynamics of Integrated Assessment Model simulations typically arise from some kind of optimization process, or simulation of some economic equilibrium. In some cases, this takes the form of a maximisation of a welfare function, while in some others the objective is to minimise the costs of the energy systems. Some of them use an intertemporal optimization method with forward-looking agents, while some others choose a recursive dynamic solution instead, where results are calculated for each time step without an explicit representation of agents' expectations.

These classes of IAMs are characterised by the highly aggregated nature of their economic modules. There is usually no distinction between the different economic agents – households, firms and government, let alone banks and monetary authorities – or different productive sectors, such as agriculture, industry and services. The assumption of a single homogeneous non-energy economic sector simplifies and improves the tractability of the models but, on the other hand, does not allow an exhaustive analysis of economic interactions. This can be done in principle by using computable general equilibrium models (CGEs), such as those based on the GTAP input-output database (Narayanan et al. 2012), but these are generally used only to examine more short-term policies.

The two models WITCH and REMIND belong to the sub-class of IAMs that simulate future dynamics through the intertemporal maximization of a social welfare function either subject to some physical constraint – an exogenous target for temperature increase or atmospheric concentration of greenhouse gases – or in a cost-benefit framework taking account explicitly of the costs of climate change. Other models that share similar features include the RICE (Nordhaus and Yang 1996), the MERGE (Manne and Richels 1992) and the FUND (Tol 1997) models.[5]

In both WITCH and REMIND, the production of the single good – used for both consumption and investment purposes – takes place through a Constant Elasticity of Substitution (CES) technology, with physical capital, labour and energy services as input factors. The elasticity of

[5] Some of these models can also be used to endogenise the exogenous target by including projections of expected social welfare, including the expected net damages (in utility terms) from climate change, and choosing a target equalizing marginal expected welfare costs and benefits of climate-change mitigation. The discussion here focuses on their use without their climate-impact modules.

substitution between inputs is assumed to be lower than one (Gerlagh and van der Zwaan 2004), implying that substitution between energy services and other inputs is difficult. The distribution of output among consumption, investment in physical capital and other energy expenditures is endogenously determined as if by a set of regional social planners with perfect foresight who maximise the sum of intertemporal discounted regional utilities, which in turn are logarithmic functions of per capita consumption weighted by regional population (Bosetti et al. 2007; Leimbach et al. 2010). The theoretical structure of the models' economic modules therefore broadly follows the standard Ramsey-type growth framework, the main exceptions being the introduction of aspects of endogenous growth theory in the WITCH model – especially regarding technical change in the energy sectors – and the representation of international trade in REMIND.

Another distinctive feature of IAMs is the long-term perspective of their analysis, with simulations usually up to at least the end of the century. That is necessary given the temporal horizon of climate-change dynamics. However, focusing on trends without considering economic fluctuations leaves IAMs with little to say about the relationship between emissions, policy settings and the shorter-term cycles of economic activity (Fischer and Springborn 2011; Heutel 2012).

Economic growth in these models is driven by two factors. First, it reflects the accumulation of physical capital, which is endogenously determined through the welfare intertemporal optimization. Second, it is also reflects exogenous trends in the technical parameters describing the productivity of input factors. In most models, the latter factor plays a predominant role; their economic dynamics are mainly determined by the assumptions made about how labour productivity and energy efficiency evolve over time (Jakob et al. 2009).

[Figure 1 about here]

The first panel of Figure 1 shows GDP year-to-year growth rates across a selection of regions[6] in the LIMITS business-as-usual scenario (Base), where no climate policy is implemented (and no explicit climate impact damages are included)[7]. There is a large variation in annual growth rates in the short term (2020) – ranging from 2% in Europe to almost 14% in China – and then a gradual convergence towards a common long-run growth rate of around 1.5-2% by 2100. The only exception is the African region, where growth rates at the end of the century are still around 4%, although on a decreasing trend. Despite the convergence of growth rates, the large

[6] We use a geographical disaggregation based on ten macro-regions: North America (NORTH_AM), European Economies (EUROPE), Pacific OECD (PAC_OECD), Reforming Economies (REF_ECON), China (CHINA+), India (INDIA+), Rest of Asian Economies (REST_ASIA), Africa (AFRICA), Middle Eastern Economies (MIDDLE_EAST), Latin America (LATIN_AM), plus a residual eleventh region, Rest of the World (REST_WORLD). For a more detailed discussion, see Massimo Tavoni, 'Policy Overview: Regional Effort for Climate Stabilization', *Climate Change Economics,* Forthcoming (2014).

[7] We report only the results for WITCH. Results from REMIND are almost identical.

disparities in starting income levels and the different population dynamics across regions inhibit the long-run convergence of per capita income. The lower panel of Figure 1 indicates divergence in individual income levels across regions, with North America and Europe clearly outdistancing all the other regions, and with Africa still lagging behind.

In all the other LIMITS scenarios, a tax on carbon is implemented as a simple way of modelling policies to discourage greenhouse gas emissions. Figure 2 shows the dynamics of the single global carbon price for both REMIND and WITCH across a range of scenarios[8]. In the Reference Policy (RefPol) and the Stringent Policy (StrPol) scenarios – where regions keep the same level of current commitments throughout the century without integrating their carbon markets – carbon prices are still very low in both models. Also, they differ across regions. In the rest of scenarios, the chosen climate policy is a global carbon tax on all Kyoto gases starting from 2025 onwards (2035 for RefPol2030-500). In these cases, carbon prices are endogenous to the model and determined through the optimisation process subject to some physical constraint. For instance, Figure 2 shows the dynamics of carbon price for two scenarios in which the Reference Policy is applied until 2020, and then a carbon price is introduced so as to achieve a concentration target of 450 (RefPol-450) or 500 parts per million of CO_2 equivalent (RefPol-500) by 2100[9]. It can be seen that the two models exhibit different results, with WITCH having a higher carbon price than REMIND throughout the period. The difference is due to varying assumptions about the potential to decarbonize the supply side of the energy sector. WITCH assumes lower mitigation potential and limited substitutability between energy sources, and relies more on a reduction of energy demand, which – given the complementarity between factors of production – induces higher carbon prices. The two models span the range of carbon prices in the LIMITS multi-model exercise, thus providing a good illustration of the extent of variation brought about by different model characteristics.

[Figure 2 about here]

2.2 Aggregate investment and its composition

Climate policies in IAMs are usually evaluated according to their *macroeconomic costs*, measured as the amount of Gross Domestic Product that is lost with respect to the business-as-usual scenario (without climate impacts) because of the implementation of the climate policy, or as the loss according to the objective function chosen (e.g. expected discounted consumption per capita). Despite being a key variable, GDP loss is insufficient to describe the more complex economic dynamics involving investment, tax revenues, public and private expenditure, trade flows, current account balances and so on. In the following sections, some of these variables are reintroduced in the discussion, while not disregarding the importance of GDP loss.

[8] For the complete set of scenarios employed by the LIMITS projects, see Table 1.
[9] Temporary overshooting of targets is allowed.

This section focuses on investment. Being designed primarily to study energy systems, many IAMs do not model economies' aggregate investment in a sophisticated way. This is probably because, for the sake of simplicity, economic growth is generally assumed to take place as a result of exogenous trends in input factor productivities and aggregate output or capital. Even energy investment has not been investigated thoroughly in the IAMs literature and has only relatively recently attracted the interest of researchers (Carraro et al. 2012; IEA 2011; McCollum et al. 2014; Riahi et al. 2012).

However, there have been a number of estimates of the incremental aggregate investment needed. For instance, the survey by Olbrisch et al. (2011) reports estimates of additional yearly investment to be employed by 2030 to keep the rise in global temperatures below 2°C. They range from a minimum of about $400 billion per year to more than $1,200 billion. According to WEF (2013), the investment required to respond adequately to the climate challenge is around $700 billion per year, from now until 2030, while UNEP (2011) estimates that the investment needed to green the economic system (and not only to stabilise temperatures) ranges from $1,000 to $2,600 billion. Kennedy and Corfee-Morlot (2012) focus on global investment needs in infrastructure. Based on OECD and IEA modelling, they suggest that the incremental global infrastructure costs of moving from a business-as-usual scenario to a low-carbon scenario in the near term (2015-2020) are likely to be between US$ 0 and US$ 400 billion per year (with savings in some sectors, due to reduced transportation and consumption of fossil fuel and increased fuel efficiency, but increases in others, including renewable power generation and buildings). The range of sectors for which investment is projected and the extent of macroeconomic adjustment envisaged differ across studies.

[Figure 3 about here]

Figure 3 reports the difference with respect to the business-as-usual scenario (Base) of cumulative investment in the period 2010-2050 in various LIMITS low-carbon scenarios. Values are discounted using a constant 5% discount rate. For simplicity, only three scenarios are reported, but the rest of the scenarios show the same key features. Total aggregate investment is divided into investment flowing into the energy sectors to provide energy-supply capacity[10] and all the other 'non-energy' investment devoted to the accumulation of physical capital. Investment

[10] In this paper we focus on 'energy-supply investment', which includes investment in: electricity generation and supply, including electricity storage and transmission & distribution; extraction and conversion of fossil fuels; production of hydrogen; production of liquid fuels; heat generation facilities; CO2 transport and storage; and other types of energy conversion facilities. Energy-supply investment coverage slightly differs between the two models. REMIND does not report investment for biomass production and fossil fuel extraction, while WITCH does not report investment for biomass production, electricity transmission & distribution, fossil liquids production and biofuels production.

for energy efficiency improvements (e.g. in buildings and transport) and investment in energy-related R&D are not included[11].

The results differ across the two models. In the REMIND model, climate policies give rise to an increase in energy-supply investment and to a simultaneous decrease in other investment. In scenarios RefPol-450 and RefPol-500, the former effect prevails over the latter, thus leading to an increase of the total aggregate investment brought about by climate policy. In RefPol, changes with respect to the business-as-usual scenario are much smaller and approximately net each other out, leading to a minimal decrease in aggregate investment. In the WITCH model, by contrast, both energy-supply and other investment decrease when a carbon price is applied, with non-energy-supply investment falling slightly more than energy-supply investment in all scenarios. The net effect of climate policies on total aggregate investment is thus unambiguously negative.

The discrepancies between the models are mainly due to different assumptions regarding the reaction of the economy to an increase in the price of carbon. A higher carbon price will have two main economic consequences. First, it will provide incentives to switch to less polluting energy sources, for which investment costs are higher than for fossil fuels (McCollum et al. 2014), thus leading to an increase in total supply-side energy investment. Second, an increase in carbon prices will depress the demand for energy, as well as overall economic activity, and consequently tend to reduce investment in energy capacity. The relative size of these two effects will determine the direction of the overall change in energy-supply investment with respect to the reference scenario with no climate policy. As noted above, the two models span the range of the LIMITS multi-model ensemble, with REMIND being more optimistic than WITCH about the long-term potential of low-carbon energy-supply resources and costs. The results reported in Figure 3 show accordingly that WITCH scenarios are characterised by a strong reduction in energy demand – which leads to a decrease in total energy-supply investment – whereas in REMIND the decarbonisation effect prevails.

Investment in other non-energy sectors exhibits the same trend across models, as it decreases with respect to the Base scenario both in WITCH and in REMIND. That happens because higher energy costs provide incentives to substitute other input factors (capital and labour) for energy. Given that the models employ a production function with an elasticity of substitution lower than one, the process causes a reduction in marginal productivity and a drop in investment in physical capital (Carraro et al. 2012). An important caveat is that changes in investment in other sectors

[11] Investment for energy efficiency improvements and investment in energy-related R&D are not included in the standard WITCH and REMIND runs, and therefore are not considered in this paper. For an analysis of demand-side investment in LIMITS, see: David Mccollum et al., 'Energy Investments under Climate Policy: A Comparison of Global Models', *Climate Change Economics,* forthcoming (2014). See also the chapters dedicated to energy efficiency of: Iea, 'World Energy Outlook 2012', (Paris: OECD/IEA, 2012).

as a result of decarbonisation policies are not considered explicitly. Nor are the investments required to increase energy efficiency in other sectors analysed. Also, the composition of gross investment will differ in practice, as different – lower carbon – technologies are embodied in new capital.

2.3 Macroeconomic cost and investment

After the brief perspective on what the LIMITS results entail for energy-supply and total investment offered above, this section discusses the link between these macroeconomic variables and the broader macroeconomic cost of climate policies, measured as the percentage deviation of GDP in the climate-policy scenario from the business-as-usual GDP. Figure 4 plots for different scenarios macroeconomic cost on the y-axis and the percentage variation with respect to the Base scenario of aggregate investment in the economy on the x-axis. All values are cumulated over the 2010-50 period using a constant 5% discount rate. The WITCH model shows an almost linear trend: as the carbon price increases and climate policy becomes more stringent, aggregate investment decreases and the loss in GDP increases. This is due both to a decrease in energy-supply investment triggered by a reduction of energy demand and to a drop of investment in physical capital caused by the lower marginal productivity of capital, which produces a decline in the level of output. Some scenario clustering is visible from the graph. The Base scenario is at the origin of the axes, as it is the reference case; RefPol and StrPol start to show both macroeconomic costs and reduced investment; all the scenarios with a 3.2 W/m^2 radiative forcing target come next, with a reduction in investment of approximately 5% with respect to the Base and a loss of GDP of 2% over the 2010-50 period; finally, the scenarios with a radiative forcing target of 2.8 W/m^2 involve a decrease of investment of around 8% and a GDP loss of around 4%.

[Figure 4 about here]

REMIND results are quite different. There is no clear sign of a negative effect of climate policies on aggregate investment. In all the scenarios, investment is between -0.5% and 0.5% compared with the Base. The loss in GDP associated with climate policies is therefore the result of a transfer of investment resources from more productive to less productive sectors. Even in the scenarios where the total amount of investment increases, the drop in aggregate productivity due to the redirection of resources towards the less productive low-carbon energy technologies is strong enough to produce a reduction in GDP with respect to the business-as-usual scenario.

Figure 5 offers a similar analysis but using just the share of investment that flows into the energy sectors to augment supply. In the WITCH model, the trend is similar to the one in Figure 4 but with a larger variation on the x-axis. Energy-supply investment decreases as the climate policy becomes more stringent and can reach a level 30% below the business-as-usual case. The results from REMIND go in the opposite direction. As the carbon price increases, energy-supply investment becomes larger and larger (up to 40% above the reference case in some scenarios). The discrepancy is due to the differences in how the two models represent the reaction of energy demand to an increase in carbon prices. While in REMIND a surge in investment in renewable energy capacity – more expensive than traditional fossil fuels – takes place, in WITCH a reduction in the demand for energy dominates, which leads to a net decrease in energy-supply investment.

[Figure 5 about here]

Finally, Figure 6 offers a more detailed look at the macroeconomic effects of climate policies in developing regions[12], comparing three different types of incremental costs: GDP loss (with respect to the Base scenario), incremental aggregate investment and incremental energy investment. The chart shows clearly that incremental investment costs can be a very misleading indicator of incremental GDP costs. The incremental GDP costs in 2020 are projected to be considerably more than implicitly acknowledged in international negotiations so far – around double the $100 billion per year agreed at Copenhagen for climate finance by 2020 from advanced industrial economies to developing countries (and these are supposed to cover adaptation costs as well as mitigation costs). By 2030, when polices are assumed to have kicked in more fully, the incremental costs are projected to be much higher still.

[Figure 6 about here]

2.4 *Investment in historical perspective*

Incremental aggregate investment needs in the 2010-2050 period (Figure 7) are not large compared with past variations in aggregate investment/GDP ratios (Figure 8). The models here suggest that investment rates are likely to increase in the short run under business as usual as well as in the various climate-change mitigation scenarios. Comparing mitigation scenarios with the base case, incremental investment needs are small. Indeed, according to the WITCH simulations, incremental investment needs may be negative, largely thanks to reduced energy intensity[13]. This reduction is induced in part by substitutions away from energy in production and consumption in response to higher prices and in part by technological progress. In the REMIND runs, incremental investment at the global level reaches a maximum of just under 1.3 percentage points, although for some regions the maximum is larger. For example, in both Africa and

[12] The developing countries group includes: Africa, China, India, Latin America, Middle East, Reforming Economies, Rest of Asia and Rest of the World.

[13] Improvements in energy efficiency require investment too, including in energy R&D, which we do not consider here. For an analysis of R&D investments in WITCH, see: Giacomo Marangoni and Massimo Tavoni, 'The Clean Energy R&D Strategy to 2°C', *Climate Change Economics,* forthcoming (2014).

Reforming Economies, required incremental investment exceeds 3 percentage points of GDP in several periods.

[Figure 7 about here]

The models considered here do not capture all the incremental investment needs of the transition to a low-carbon economy, as they concentrate on the necessary changes in energy supply and the consequent general equilibrium changes in aggregate investment. They do not take account of the need for countries to invest to adapt to climate change, although the costs of so doing could easily be of a similar magnitude to the costs of mitigation (Narain et al. 2011). Nor is incremental investment to reduce the demand for energy systematically considered, although this is likely to have to be substantial. For example, incremental investment needs in the transportation and buildings sectors are not fully modelled, although they are likely to be large (Kennedy and Corfee-Morlot 2012). McKinsey & Company (2009) estimated that additional investment in energy supply by 2026-30 to keep below the 2°C ceiling would amount to only about one fifth of the total incremental investment needed, with transport (e.g. electric car production) and buildings (e.g. higher standards of insulation) accounting for over 60%. Work for the UNFCCC also suggested only about one fifth of the total incremental investment needed would be in energy supply once allowance is made for reduced investment in the fossil-fuel sector; the IEA (2009) projected the fraction would be even lower (see Table 1 and its discussion in Olbrisch et al. 2011). The ADAM project's estimates of the investment needed to bring about a transition to a low-carbon economy in Europe suggested that over four times as much extra investment would be required for buildings than for energy supply (Hulme et al. 2009). The estimates of incremental investment needs also show considerable variation across regions, while the differences in the REMIND and WITCH results draw attention to the substantial uncertainty about such projections.

Nevertheless, the estimates are consistent with the view that the costs of staying below the 2°C ceiling, which include the consumption costs incurred if and when investment crowds out consumption, need not be prohibitive – if policy is implemented cost effectively and is not delayed. As the models allow for the substitution of capital for energy in response to the higher relative price of energy, a larger share of non-energy-supply investment is implicitly devoted to more energy-efficient technologies even though this process is not modelled separately from other (general equilibrium) changes in non-energy-supply investment. The REMIND and WITCH results are broadly in line with several studies that have considered aggregate mitigation costs, such as Stern et al. (2006), the RECIPE project (Edenhofer et al. 2009) and the ADAM project (Knopf and Edenhofer 2012). The estimates are less optimistic than some of the 'bottom-up' estimates in the literature, such as those in McKinsey & Company (2009) and Chapter 9 of Stern et al. (2006), even though the latter two explicitly include changes in investment in a broader range of sectors. The estimates reflect a more optimistic outlook than do a number of other aggregate studies, however, such as those compared in the EMF22 modelling exercise[14].

Figure 8 shows how investment ratios for various regions have varied since 1980 (IMF 2012). The standard deviations of these time series (Table 2**Errore. L'origine riferimento non è stata trovata.**) vary from just over 1% to over 5%, showing that significant variations in the level of investment – in most cases, well above the incremental investment needs computed for scenarios in the REMIND runs – have been successfully financed in the recent past. Investment ratios have tended to be considerably higher for many emerging-market economies than for high-income countries. India and China in particular have demonstrated how changes in broad economic policy – deregulation and integration into the global economy – can generate large increases in aggregate investment rates.[15] Specific exogenous shocks to economies, such as the increase in demand for Australian coal and minerals (Bishop and Cassidy 2012), have also been known to stimulate aggregate investment rates. Pioneering efforts to measure and model broader 'green investment' flows show that green investment has been a major impetus behind total energy-supply investment in recent years across countries and China has accounted for a large part of the increase in green investment (Eyraud et al. 2011) [16]. Thus, where and when increases in investment are required for climate-change mitigation, the pace of the necessary increases is by no means unprecedented. This stands in contrast to the speed of global reductions in annual greenhouse gas emissions that will ultimately be required to stay below the 2°C ceiling, which is without precedent.

[Figure 8 about here]

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[14] See the 2009 special issue of Energy Economics, in particular Leon Clarke et al., 'International Climate Policy Architectures: Overview of the Emf 22 International Scenarios', *Energy Economics,* 31, Supplement 2/0 (2009), S64-S81.

[15] For example, reported Chinese investment increased by over seven percentage points of GDP between 1992 and 1993, while reported Indian investment rose by nearly 15 percentage points between 2001 and 2007.

[16] They find that green investment is boosted by economic growth, a sound financial system conducive to low interest rates and high oil prices. They also find that some policy interventions, such as the introduction of 'feed-in tariffs' that require use of green energy, have a positive and significant impact on green investment but some others, such as support for biofuels, do not.

3. The role of public finance

3.1 Rationale for the use of public finance mechanisms[17]

Climate-change mitigation entails a change in the composition of investment, with a greater proportion going to energy supply, energy distribution and improved energy efficiency, as explained above. Although aggregate investment may not have to rise in total – the LIMITS consortium's models disagree about this – public policy needs to bring about a change in the direction of investment. At the same time, public policy needs to underpin carbon pricing as widely as possible as the key instrument to implement mitigation. This raises the question, how should governments' tax and spending powers be used to provide financing mechanisms to support climate policies?

Public finance mechanisms are not essential in theory but are likely to be important in practice, as Bowen (2011) argues. He notes that there is a simple textbook prescription to deal with the greenhouse gas externality that would rely wholly on private finance mechanisms. A global cap-and-trade system with appropriate allocation of tradable emissions quotas across individuals, firms, countries and time, would entail a reliance on private sources of finance would generate a world price for emissions, so that private agents would internalise the externalities they cause. The lump-sum transfers across individuals necessary to correct any adverse distributional impact from the imposition of a price and the residual climate damages would be achieved by appropriate initial allocation of quotas. The allocation could also be used to compensate those who had to spend proportionally more on adaptation to climate change. Private finance flows would be generated entirely in carbon markets. Local investment in mitigation and adaptation would be financed by firms and households, with the help of revenues from carbon markets and guided by the changes in relative prices over products and across time induced by the carbon price. The role of the state would be limited to creating the property rights in emission quotas and regulating carbon markets.

However, this textbook prescription is highly unrealistic. First, it would be very difficult to ensure that the private rents created by the free issue of quotas would be appropriately distributed. There would be a danger of reinforcing the market power of incumbent firms. Allocating some quotas directly to households to compensate for increases in energy prices, taking account of their regressive nature, would be highly complicated.

Second, adequate private investment in the low-carbon transition would still be discouraged by any lack of confidence on the part of private agents that the climate policy framework would be

[17] This sub-section draws heavily on Bowen (2011).

strengthened over time. Long-term credibility would be enhanced if people know that policy-makers' tax revenues are going to be partly dependent on maintaining the framework. Policy commitments that include reputational or financial incentives for governments to achieve promised outcomes can enhance the credibility of the commitments and help to align the interests of policy-makers more closely with those of private agents.

Third, climate-change mitigation requires collective action against a range of market failures, in some cases taking the form of public subsidies to ensure that incentives to private agents are aligned with public objectives. Examples include support for low-carbon research and development, pump-priming support for the creation of network infrastructure supporting the low-carbon transition (such as electric vehicle charging networks and pipelines for carbon capture and storage), risk-mitigating co-finance for energy infrastructure projects and the provision of energy efficiency information. The public sector can redirect innovatory activities by supporting the development of low-carbon technologies that have not yet benefited from extensive experience. With respect to network creation, it may be easier for the public sector to set up the network rather than to calibrate and apply the appropriate initial subsidies to stimulate private provision. When private-sector financial intermediation is impaired (as it still is in many countries at the moment) by reduced risk appetite, heightened doubts about counterparty solvency and increased uncertainty about asset valuations, the public sector may need to act as a financial intermediary of last resort.

All such interventions require extra revenues. Public finance theory gives some guidance as to the mechanisms required. First, the taxation of environmental 'bads' is an efficient way to raise such revenues. Taxes should be levied on 'bads' such as emissions and congestion - so-called 'Pigovian' taxes (Pigou 1932). If that generates insufficient revenue, 'goods' in more inelastic supply should be taxed more heavily. This suggests the desirability of working out how to tax 'bads' that are currently escaping the fiscal net, hence the potential role for carbon taxation.

Second, public authorities have a choice between raising taxes (or fees and user charges) and borrowing to finance expenditures. The general principle suggested by public finance theory is to tax to finance current spending and borrow to finance public investment; the social return on the investment should be expected to exceed the cost of raising funds (Blanchard and Giavazzi 2004; Ismihan and Ozkan 2008). Hence increased social benefits to compensate poor households for higher energy prices should be financed by higher taxes while public investment in long-lived energy and transport infrastructure should be paid for by increased borrowing. If the case for countercyclical deficit financing by governments is accepted, this justifies a greater share of borrowing in the downturn of the business cycle, but an 'exit strategy' to substitute other funding sources is necessary if the associated spending is to continue during recovery[18]. Another

[18] The relationship between environmental policy and business cycles is discussed in Bowen and Stern (2010).

justification for more borrowing is if the government is in a better position than banks to act as a financial intermediary, for example because there are risks that can be better assessed and managed in the public sector – one of the arguments for public-sector sponsorship of 'green' investment banks (GIB 2010).

Third, taxes raise questions of equity as well as efficiency. The ultimate incidence of new carbon taxes or quota auctions therefore needs to be considered and, if necessary, the welfare system adjusted to compensate losers. In practice, this is often difficult without changing incentives and thereby affecting economic efficiency. Advani et al. (2013) provides a good example of proposals, for the United Kingdom, to compensate for higher energy prices induced by climate policies.

Fourth, traditional public finance theory discourages hypothecation of revenues from particular sources to particular uses, except when setting a user charge to cover the marginal costs of a publicly provided good (McCleary 1991; OECD 1996). With the latter exception, there is no reason why the revenue generated by the appropriate tax rate on one activity (e.g. global greenhouse gas emissions) should equal the appropriate spending on another activity (e.g. optimal spending on adaptation and mitigation at the chosen target level of GHG concentrations in the atmosphere). Even if tax rates and spending are initially set so as to bring about the equality needed, there is no guarantee that this will remain the case over time. Indeed, the so-called 'double dividend' literature is predicated on the possibility that revenues from carbon taxation (or quota auctions) could also be used to reduce distortionary taxes, such as payroll taxes, elsewhere in the economy. The mere fact that two activities are climate-related does not justify earmarking the revenues from taxing one of them for spending on the other.

In the context of climate finance for developing countries, some have argued that hypothecation is likely to make it easier to ensure that funds raised are additional to previous commitments by developed countries (Müller 2008; Oxfam 2008). However, finding a new source of revenue and then earmarking it does not prevent the earmarked spending from displacing spending financed from other sources of tax revenue on the same objectives. Additionality is not guaranteed by how the funding is raised (Landau 2004).

Fifth, public finance theory flags the importance of administrative costs, including compliance and monitoring costs, so it is helpful to consider whether proposals entail new administrative burdens or use the most efficient existing tax-raising and disbursement channels. Taxes applied to a broad base, but at low rates, are attractive in this respect to keep tax avoidance activities low. That points to the desirability of pervasive but homogeneous carbon pricing across economies.

3.2 Carbon tax revenues and fiscal self-reliance

In every LIMITS scenario except the business-as-usual one, a price on carbon is implemented as the policy instrument designed to bring about emission reductions. A carbon price entails fiscal flows, usually from the private sector (especially firms in energy-intensive industries) to the government, so the issues raised in the sub-section above are pertinent. A steadily rising price on carbon is likely to have strong effects on the rest of the economy and the behaviour of economic agents through relative price and income effects on those taxed, influencing the composition of consumption, investment and trade (Goulder 1995; MacKenzie and Ohndorf 2012). But in practice it will also affect the economy through the effects generated by the use of tax revenues. Unfortunately, the high degree of aggregation of economic systems typical of IAMs does not allow a detailed investigation of fiscal effects, as no clear distinction is made between tax payers and tax receivers. Usually, it is simply assumed that tax revenues are entirely recycled back into the economy by means of lump-sum transfers to households.

[Figure 9 about here]

Carbon tax revenues are equal to the price of carbon multiplied by the quantity of emissions of Kyoto gases, expressed in terms of CO2 equivalence. On one side, the increasing trend in carbon prices drives revenues up; on the other side, the decrease in polluting emissions that takes place in most of the scenarios erodes the tax base. It is not clear analytically which one of the two effects will prevail and when.

Figure 9 shows the trajectory of revenues from carbon taxation as a percentage of global GDP. In the WITCH model, the trajectories in the policy baselines RefPol and StrPol slowly increase and then stabilise around 1-2% of GDP. In the RefPol-450 and RefPol-500 scenarios, tax revenues increase much more, peaking at around 12% and 6% around the middle of the century. They then decrease to around 8% and 5% by 2100. The REMIND model shows similar trends in RefPol and StrPol, although values are lower and below 1% by the end of the period. However, its results are clearly different from WITCH for the RefPol-450 and RefPol-500 scenarios. After a steep increase before 2030, tax revenues drop quite quickly and reach approximately 3% of GDP by 2050. They eventually become negative by the end of the century, reflecting the fact that subsidies have to be paid to 'negative emissions' producers[19]. The RefPol-450 scenario, which is more stringent than RefPol-500 since the radiative forcing target is lower, delivers the highest tax revenues in WITCH and is the scenario implying highest subsidies in REMIND. The strong difference between the two models is motivated by the different dynamics of carbon prices – shown in Figure 2 – on one side, and by the paths of optimal emissions on the other, as in REMIND emissions become negative by the end of the century.

[19] By 'negative emissions' is meant the permanent removal of greenhouse gases from the atmosphere through carbon capture and storage (CCS) technology.

The figures for carbon tax revenues seem ambitious considering that the revenues from the entire set of environmentally related taxes in 2004 were approximately equal to 1% in North America, 2.6% in the EU15 and 1.8% on average across all OECD countries. The OECD average rate had actually fallen a little by 2008, to around 1.7% (OECD 2008). Nevertheless, general government revenues in 2010 accounted for approximately 36% of GDP in advanced industrial economies and 27% in emerging and developing countries (IMF 2012). A reform of fiscal policies could therefore generate, with relatively small effort, carbon tax revenues similar to the ones depicted in Figure 4. It is also important to remember that the large carbon revenue figures are obtained in the case of climate policies that achieve the 2°C target with sufficiently high probability. These are thus very ambitious and stringent climate scenarios, imposing radical changes on the way energy is consumed and produced.

[Figure 10 about here]

Figure 10 presents the dynamics of the global 'energy fiscal surplus' – that is, the difference between investment flowing to the energy sectors to augment supply and revenues from carbon taxes levied on those sectors, both expressed as shares of Gross Domestic Product. The goal is to assess the capacity of economies to find the cash flows necessary to finance the energy-supply investment they require by raising carbon revenues. Values below the x-axis are characterised by having carbon tax revenues lower than investment in energy supply; values above the axis indicate that carbon tax revenues are larger than the optimal energy-supply investment in the same scenario. In other words, the position on the plane offers a sense of the 'fiscal self-reliance' of the energy sector (although the diagram does not take into account the investment required for enhanced energy efficiency in the economy).

Until 2020, the absence of a global carbon tax makes the energy system fiscally dependent on the rest of the economy in all the scenarios, implying that the regional carbon prices applied in the short term are not sufficient to cover the necessary energy-supply investment. Hence the sector initially needs to find other sources of finance. This applies to the whole 2010-50 period presented in Figure 5 in the case of the RefPol scenario, and in the StrPol scenario according to REMIND (WITCH values for StrPol scenario become slightly positive from 2040 onwards). However, the RefPol-450 and RefPol-500 scenarios, in which an optimally determined global carbon price is implemented from 2025, show very strong fiscal self-reliance of the energy system, meaning that the needed energy-supply investment can be financed through the carbon-tax revenues without resorting to other sources. This is particularly true in the WITCH model, which shows an energy fiscal surplus of almost 12% by the middle of the century in the most stringent scenario RefPol-450. REMIND values are lower and on a declining trend (and eventually become negative once again towards the end of the century because of negative emissions).

[Figure 11 about here]

Figure 11 expands the analysis of fiscal self-reliance of the energy sector through a regional disaggregation of the domestic 'energy fiscal surplus'. For each region, the results are reported for both models (REMIND values on the left with solid markers and WITCH on the right with dashed markers) and for two representative scenarios, RefPol and RefPol-450.

The results for RefPol, a scenario in which only governments' current commitments are implemented in the future, show 'energy fiscal deficits' across all regions, with the notable exception of Europe, meaning that the revenues raised through the introduction of a carbon price are not sufficient to finance the necessary investment in increasing energy supply. Some other source of finance would have to be found in order to do that. In particular, according to WITCH, the deficit appears to be very large in the Middle East region (-9%) and, to a lesser extent, in the Reforming Economies (-4%).

In contrast, the introduction of a global carbon tax on polluting emissions capable of achieving a radiative forcing of 2.8W/m2 by the end of the century and a high chance (>70%) of staying below the 2°C ceiling – as contemplated by RefPol450 – is likely to ensure domestic energy fiscal self-reliance in all regions. In 2030, carbon tax revenues are able not only to finance all energy-supply investment, but also to provide a surplus available for other non-energy-supply-related purposes. The results show a degree of consistency across models, with developing regions exhibiting much higher domestic fiscal surpluses than high-income ones. However, REMIND values tend to be lower than WITCH ones, in some cases by as much as 10%. This discrepancy increases in following decades because of the different dynamics of carbon tax revenues (increasing in WITCH, declining in REMIND).

The large differences between the RefPol and RefPol-450 scenarios in both models are mainly due to the much higher tax revenues rather than to the change in energy-supply investment requirements with respect to the business-as-usual scenario, underlining the fundamentally different nature of moderate climate-mitigation scenarios compared with the 2°C ones.

3.3 The economic value of land use emissions

This section goes beyond carbon pricing in the energy supply sector and investigates the financial implications of carbon pricing applied to the CO_2 emissions generated by land use and human-induced changes in land use. This category includes emissions related to pasture conversion, deforestation, afforestation, reforestation, soil management and other activities related to land use. The focus is on net land-use emissions, taking account of the potentially important role of appropriate land use in providing carbon sinks.

Figure 12 reports the projections of global CO2 land-use emissions of the LIMITS models, cumulated over the 2010-2050 and 2050-2100 periods. Two scenarios are considered: RefPol, which applies the current mitigation commitments of governments over the whole century, and RefPol-450, in which a stringent climate policy is implemented to ensure a high probability that the 2°C ceiling in global temperature increase is not exceeded.

[Figure 12 about here]

In the medium term, up to 2050, most of the models show a positive cumulative value of net CO2 land-use emissions. The trend of emissions is decreasing throughout the period, but most models still have positive land-use emissions by the middle of the century. This is true for both the RefPol and the RefPOl-450 scenarios. The only exception is with the GCAM projections, where emissions from land use become strongly negative starting as soon as 2030, especially in the RefPol-450 scenario. This is due to the fact that GCAM includes an explicit monetary incentive to store more carbon in the terrestrial system, resulting in an increase in forest cover and negative land-use change emissions.

During the second half of the century, land-use emissions continue to decrease and by the end of the century become negative according to most of the models, meaning that the role of land and forests as carbon sinks dominates by then. This leads some models to have negative cumulative emissions in the 2050-2100 period for the RefPol scenario (GCAM, IMAGE and MESSAGE), and all of them (except IMAGE) in the scenario with the most stringent climate policy.

Differences between the two scenarios are sometimes quite large, as in the case of GCAM for the 2010-2050 period or MESSAGE for the second half of the century. In the vast majority of cases, a stringent climate policy brings about a decrease in land-use emissions with respect to the reference baseline. The only exception is IMAGE, where the implementation of climate policies induces an increase in land-use emissions. This is due to the fact that in IMAGE the switch to bioenergy is an important driver of the overall reduction in energy-related emissions.

The economic implications of a change in land-use emissions caused by the implementation of climate policy can be examined by carrying out an exercise similar to that reported in section 3.2, relating the carbon-price dynamics to the dynamics of land-use emissions. The results are shown in Figure 13, where the economic values of land-use emissions in the RefPol-450 scenario are reported. Negative values can be interpreted as subsidies flowing to the owners of land in order to use their land as carbon sinks. The economic values in the RefPol case are much smaller, because of the massive difference in carbon prices between the two scenarios (see figure 2).

Negative emissions combined with high carbon prices produce strong negative values, especially towards the end of the century, suggesting the potential for large inward finance flows for the developing countries with a large share of the reduction in emissions from land use but also fiscal challenges for domestic carbon pricing schemes. There is a high degree of variability across models, with IMAGE and REMIND ending the century just below the zero and MESSAGE reaching 4% of global GDP.

[Figure 13 about here]

The change in land-use emissions produced by climate policy is likely to affect different geographical regions in different ways. Areas covered by large forests, such as Latin America or Indonesia, are usually the regions where the models suggest that most of the change in emissions could take place. Figure 14 reports the difference in land-use emissions between the RefPol-450 and the RefPol scenarios, cumulated over the 2010-50 period . The chart confirms that the region where most of the reduction in land-use emissions is likely to take place is Latin America. This is due to both to avoided deforestation and potential for reforestation. The result is consistent across models, with the exception of IMAGE, which displays an increase in emissions as a consequence of the potential of the continent to produce bioenergy. Other major contributors to the decline in emissions, although on a much lower scale, are Africa and Rest of Asia.

[Figure 14 about here]

Figure 15 reports the economic value attached to the change in land-use emissions driven by climate policy, cumulated over the 2010-50 period. The pattern shown is not uniform, especially for certain geographical regions. Latin America, for instance, experiences an increase in land-use emissions according to IMAGE, WITCH and REMIND, despite the decrease in emissions highlighted above. This means that in these models the increase in carbon prices in Latin America (between RefPol and RefPol-450) more than compensates for the decrease in land-use emissions. This, on the other hand, does not happen in either MESSAGE or TIAM-ECN, which display a decrease in the economic value of land-use emissions. Reforming Economies also show mixed results, with IMAGE and TIAM-ECN reporting an increase in value, and all the other models reporting a decrease.

Results are more consistent for other regions. China, for instance, experiences a reduction in the cumulative economic value of land-use emissions, in all models and especially in the WITCH case. In the Chinese case, land-use emissions remain the same but, since they are quite strongly negative, the increase in carbon price produces a flow of subsidies to the owners of land. The results for Africa are also quite clear, showing a strong positive change. In this case, the carbon price effect predominates, and in the case of IMAGE is combined with the effect of having higher land-use emissions after the implementation of the policy. These can be interpreted as a flow of revenues to governments.

[Figure 15 about here]

3.4 The outlook for environmental taxation

In the LIMITS scenarios, carbon tax revenues are projected to amount to between 0% and 6½% of GDP, a similar amount, or more than, the current level of *all* environmentally related taxes in the OECD as a whole (according to the OECD, environmental taxes in the OECD amounted to around 2% on a weighted-average basis in 2010 and reached a maximum of around 4%, in Denmark).[20] A gradual increase in the relative size of such revenues is projected in most scenarios and models to around 2060/70. In REMIND RefPol-450 and RefPol-500, the decline of polluting emissions triggers a significant drop in revenues after reaching a peak, a challenge for fiscal policy-makers seeking stable sources of revenue.

To achieve this level of taxation will be a substantial challenge to all countries, given political resistance to increasing tax burdens as a proportion of GDP. There are also issues of enforceability and comprehensiveness, for example, with respect to carbon taxes on agricultural greenhouse-gas emissions, land-use change and deforestation and to taxes on other greenhouse-gas emissions that are more difficult than carbon dioxide to monitor. Even the attribution of CO_2 fluxes to certain activities, such as deforestation, is difficult and uncertain. But the projections illustrate the potential for offsetting reductions in tax rates elsewhere in the economy, shifting the burden from 'goods' such as employment to 'bads' such as environmental pollution, a shift advocated by the World Bank and others as part of fiscal reforms for developing countries (World Bank 2005). Such a shift has the potential to increase productivity by reducing fiscal disincentives to the efficient allocation of factors of production, a macroeconomic link rarely present in IAMs.

[20] Data are available from www2.oecd.org/ecoinst/queries/index.htm.

4. The role of credit in stimulating private finance

As the previous section argued, one of the conditions to be met in order to achieve a low-carbon economy is the existence of a fiscal system capable of aligning the incentives facing economic agents with the objective of promoting the low-carbon economy. This is the aspect of financing mechanisms on which research has focused most, from the perspectives of both policy and economic theory (Baumol and Oates 1988; OECD 2013). There is now a general agreement among scholars that policies such as imposing a tax on greenhouse gas emissions, phasing out subsidies to fossil fuels, and introducing feed-in tariffs in support of renewable energy could help to improve the environmental resilience of the economic system while at the same time increasing its overall efficiency. Such instruments should be coordinated, requiring an extensive reform of tax systems (Green Fiscal Commission 2009; OECD 2010).

However, a well-designed fiscal system is likely to be insufficient to guarantee that low-carbon sectors of economies prosper. An equally important factor is the availability of credit. Even in a scenario where fiscal incentives strongly support the growth of low-carbon sectors, so that firms are willing to invest in them and consumers to purchase their products, no activity will take place unless credit is made available. And, under certain macroeconomic conditions, credit may not flow to the sectors of the real economy that need it, even in the presence of superficially attractive prospective rates of return.

In modern economic systems, credit can be extended to support low-carbon activities in two main ways. First of all, existing credit – that is, the stock of credit previously created – can be reallocated by agents that happen to hold it. In the case of low-carbon investment, the potential role of institutional investors – pension funds, insurance companies and mutual funds, sovereign wealth funds, and other non-bank organizations managing large amounts of money on behalf of their clients – in providing finance has been discussed (Della Croce et al. 2011; Nelson and Pierpont 2013). The second way to make credit flow to low-carbon sectors is to create it *ex nihilo*, which is a prerogative of the private banking system. Credit creation takes place with the act of lending. When a bank decides to grant a loan to a client it does so by expanding its own balance sheet and the client's by the same amount. The deposit that the bank has put at the disposal of its client will then be employed to purchase whatever goods and services are desired, thus introducing the money in circulation in the wider economic system (Bernardo and Campiglio 2013).

Unfortunately, as the following sub-sections argue, neither credit mechanism appears to be allocating sufficient credit to investment in key low-carbon sectors at the moment if emission reduction targets are to be met. The question for governments is, to what extent can this be remedied by policies to price carbon and correct market failures in the provision of private finance?

4.1 Mobilisation of institutional investors

Institutional investors' existing financial assets, currently owned or managed by them, could easily provide the required finance for the transition to a green economy. Della Croce et al. (2011) estimate that assets of as much as $71 trillion are currently managed by institutional investors in the OECD countries. Some of these financial resources can be directed towards low-carbon investment in a variety of ways, either directly or through some intermediary such as private equity funds. For example, investors can decide to buy shares of companies operating in the low-carbon sectors, or purchase their corporate debt; the same can be done for single projects. Or investors may prefer to purchase bonds issued by development banks, which can then use the money to finance green projects.

Some institutional investors are interested in investing in green activities for ethical reasons, aiming at achieving a social and environmental return on top of their own financial return. Socially responsible investments (SRI) have been strongly expanding in recent years (Eurosif 2012; GIIN 2013), but they are still a niche market compared with the asset management system as a whole. In order for low-carbon sectors to obtain a critical mass of finance, it is crucial also to attract investors who are *not* moved by ethical reasons, but just by the desire for economic return.

Unfortunately, however, low-carbon sectors are currently not particularly attractive to investors interested in maximising their risk-adjusted returns. Investment in renewable resources decreased in 2012 and 2013, after ten years of sustained growth, according to Bloomberg New Energy Finance (FS-UNEP and BNEF 2013). Investment in listed renewable energy companies decreased by 60% in 2012. Share prices, as measured by the Winderhill New Energy Global Innovation Index (NEX) or BNP Paribas Renewable Energy Index, have been performing consistently worse than Nasdaq and S&P500 indices during the past three years. Many companies in low-carbon sectors have been in difficulties. For example, Suzlon Energy, Indian's largest turbine manufacturer, has had to default on a $200 million convertible note. Many manufacturers in the solar power sector have failed, including the German company Q-cells, formerly the world's largest PV maker, and the US company Solyndra, despite generous support from the federal government. Venture capital supply has also declined.

This has much to do with the policy environment, which has not been as transparent and predictable as it needs to be to attract investors into the field. Many governments have not convincingly committed themselves to long-term policies and are now reducing support to low-carbon sectors because of the stress on public finances imposed by the economic crisis. In some cases, governments have introduced retroactive adjustments – as in the recent Spanish case – reducing government credibility with respect to promised climate policies for years to come (FS-

UNEP and BNEF 2013). It is inevitably tempting for governments to try to incentivise behaviour by the promise of future payments (e.g. subsidies to renewables) or other price signals (e.g. carbon pricing) and then renege after private investment decisions have been taken, in order to reduce public finance costs (as with renewables support) or unpopularity (from, for instance, higher energy costs). From the perspective of private investors, they face the policy risks of lack of government commitment, time inconsistent behaviour by public authorities and difficult-to-predict decision-making due to the fact that a government does not behave like a single rational economic agent but instead aggregates and trades off the preferences of a range of disparate stakeholders. Hence it is important that policy-makers find ways of expressing their commitment to the climate-policy regime, for example, through underwriting the political risks, co-investing with the private sector and setting up 'reputational investments' such as statutory underpinning of emission reduction goals.

On top of this, low-carbon sectors suffer from many other uncertainties and risks. Some are specific to these and just a few other sectors, for example, the dependence of returns on the future provision of appropriate energy infrastructure. Some are shared with other sectors, for example, uncertainty about future costs due to the novelty of emergent technologies and, in some cases, the need for large upfront investment with long pay-back periods (typical of much infrastructure investment). As a result, many low-carbon projects appear to offer private investors an unattractive risk-return trade-off (Holmes et al. 2012; IFC 2011; Nelson and Pierpont 2013; WEF 2013).

Also, the market for credit to low-carbon sectors is still relatively small and illiquid, as only a very limited range of financial instruments dedicated to low-carbon investments exist. 'Green' bonds – fixed-income instruments that are issued specifically to finance low-carbon productive activities – have the potential of overcoming this obstacle, especially if issued in large amounts and in a standardised fashion. The market is expanding, and the outstanding amount of green bonds is now around $346 billion (CBI 2013). About two thirds of these pertain to the transport sector, where China alone issued $117 billion worth of bonds to finance its high-speed railway system.

4.2 Bank credit

Bank lending is typically the most important source of external financing for businesses (Eickmeier et al. 2013), especially for small enterprises and in emerging markets. The process of net credit creation by the private banking system has stalled in recent years (BIS 2013b). The lack of new credit is the result of the interaction of two complementary factors. On one side, demand for credit from the private sector is weak, as both households and non-financial

corporations have been shunning risk, postponing investment and attempting to reduce debt. On the other, the supply of credit by private banks has been tightly constrained[21].
Both these conditions are a direct consequence of the lack of confidence that is afflicting economic agents. The private sector – households, non-financial firms and financial institutions – is currently experiencing a robust process of *deleveraging*: rather than spending, agents prefer to postpone investment and save their income in order to repay the previously accumulated debt, or to protect themselves from possible future downturns. Far from maximising their profits, they are instead trying to reduce their debt by shrinking their balance sheets (Koo 2011; Zenghelis 2012). The situation in which all economic agents simultaneously attempt to save is usually referred to as the 'paradox of thrift' (Keynes 1936). What is wise from a microeconomic perspective – a household or a firm trying to reduce its over-indebtedness by reducing spending and increasing savings – can have very adverse consequences from a macroeconomic point of view. The lack of private demand at a time of crisis further worsens the situation by causing a drop in investment, forcing firms out of the market and workers into unemployment. This is not dissimilar to what happened in the wake of the global financial crisis of 2008, leading to the current situation in which unemployment remains high, output remains well below potential and growth, in many countries, is below the trend rates prevalent before the crisis (IMF 2013).

[Figure 16 about here]

Figure 16 shows the financial balances of private sectors in the euro zone, the United States and the United Kingdom. The financial balance is the difference between income and spending. If a sector spends more than it earns, there will be negative financial balance (a deficit); if spending is less than income, the sector accumulates savings, thus running a financial surplus. It is clear from the chart that private sectors in developed countries have all reacted to the financial crisis by running very high financial surpluses. In other words, they are trying to deleverage by increasing their flows of saving.

The process concerns not only households and non-financial corporations, but also banks and financial institutions. In their case, deleveraging takes the form of a constraint on credit creation, which helps keep the size of their balance sheets under control. As a consequence, and despite the interventions of the major central banks, lending has been stagnating since the financial crisis, with firms struggling to get access to credit. This is confirmed by Figure 17, which compares the recent dynamics of narrow and broad money for the euro zone, the United States and the United Kingdom[22]. The effect of Quantitative Easing (QE) measures[23] on narrow money

[21] See for instance: Bis/Niesr, 'Evaluating Changes in Bank Lending to Uk Smes over 2001–12 - Ongoing Tight Credit?', (London: Department for Business, Innovation and Skills, 2013).
[22] 'Narrow money' (or 'monetary base') comprises cash – notes and coins – and central bank reserves, the counterpart to the deposits that private banks hold at the central bank, employed by private banks to settle interbank transactions. 'Broad money' is instead the wider aggregate of bank credit, that is purchasing power created by the private banking system. See Josh Ryan-Collins et al., *Where Does Money Come From? (2nd Edition)* (London: New Economics Foundation, 2011).

is evident, especially for the USA and the UK. The amount of central bank reserves has risen steeply as a result of the Federal Reserve and Bank of England interventions in the markets. However, the stocks of broad money in these countries have remained substantially flat, indicating that the banking system is still not lending to the productive economy as much as bank regulators were hoping.

[Figure 17 about here]

4.3 Effects of new financial regulation

While tight bank lending behaviour has primarily been a reaction to worsening market conditions, the current process of financial regulation is either playing an important role in affecting banks' credit creation or will do so in the near future. New financial regulations have been formulated in recent years ('Basel III'), introducing tougher requirements for banks with respect to both the liquidity of their assets and the robustness of their capital (BIS 2013b, 2013a).

Liquidity rules require banks to hold enough liquid assets to weather successfully a prolonged funding stress scenario and to match long-term assets – with maturity over a year – with similarly long-term liabilities. Capital regulation imposes a range of minimum ratios of banks' own capital to their stocks of assets, in some cases adjusted according to their assets' degree of risk. The objective in this case is to prevent excessive leverage in the banking system, which can pose systemic risks to the functioning of economies.

The financial reform is likely to reduce the already problematic access to finance of low-carbon sectors (Spencer and Stevenson 2013). For example, liquidity requirements will most probably produce a reallocation of investment towards liquid shorter-term assets, while low-carbon initiatives typically require long-term bank credit. In general, banks are likely to reduce their demand for riskier assets, preferring to invest in very liquid and more standardised assets such as sovereign bonds rather than in projects, such as many low-carbon projects, characterised by a range of technological, financial and policy uncertainties,.

The new rules concerning capital are also likely to have a negative impact on low-carbon investment, as they would tend to reduce bank lending across all productive sectors, including the

[23] As a reaction to the crisis, major central banks have attempted to stimulate credit creation, first by lowering their reference interest rates to almost zero and then, in view of the apparent ineffectiveness of these measures, by resorting to 'unconventional' monetary policies. These have taken the form of 'quantitative easing' (QE), an expansion of central banks' balance sheets through the creation of new reserves at the disposal of the private banking system – achieved through the simultaneous purchase of financial assets, typically government bonds, from the secondary market – in the hope that financial institutions would resume their lending to businesses (See Brett W. Fawley and Christopher J. Neely, 'Four Stories of Quantitative Easing', *Federal Reserve Bank of St. Louis Review,* 95/1 (2013), 51-88.).

low-carbon ones. There are only two strategies available to banks with capital ratios – below the new minima: the first one is to increase their capital by issuing new shares or retaining profits; the second is to reduce the expansion of their balance sheets, by constraining new credit creation and making it more expensive or by selling their assets. For those capital ratios where assets are weighted according to their risk, banks can also improve their situation by reallocating their portfolios towards less risky assets, as they are already doing. None of these developments are likely to be beneficial for low-carbon sectors.

It is unclear to what extent this flight to liquid low-risk short-term assets is taking place because of financial regulation or as a market-driven reaction of the banking system to the current economic situation. Banks do not seem to be finding it difficult to meet the new regulations (Cohen 2013). However, new financial rules should be assessed over an extended period of time. The fact that they are not currently acting as a binding constraint does not necessarily mean that they will not play that role once the deleveraging process terminates and private agents start to borrow and spend again. Hence public support for low-carbon projects via some proportion of direct funding and the underwriting of risk, particularly large tail risks and long-dated risks, may become more necessary. The benefits of a successful transition to a low-carbon economy will accrue across the whole of society, so it is appropriate that the climate-policy-related risks facing private investors along the way are mitigated. In these circumstances, policy-makers need to build private sector confidence in the future growth of markets for low-carbon energy, goods and services. This can be done in part through direct government spending and in part through broader government behaviour consistent with expectations of meeting climate policy objectives (setting carbon prices, introducing mechanisms to facilitate monitoring of government performance against plans, tackling related market failures in innovation and so forth).

4.4 Public development banks

One set of economic actors that could help to unlock the flow of credit towards low-carbon sectors is the public development banks. Development banks are financial institutions characterised by a strong public component and dedicated to supporting the process of economic development by lending in key sectors, usually at lower rates than commercial banks are willing to offer (at least, in the absence of such development bank lending). They can be incorporated in some international institutions – multilateral development banks such as European Investment Bank (EIB), the International Bank for Reconstruction and Development (IBRD) and the Asian Development Bank (ADB) – or be owned by national governments[24]. These include, to cite some of the largest, the China Development Bank (CDB), the German Kreditanstalt fur Wiederaufbau (KfW) and the Brazilian Banco Nacional do Desenvolvimento (BNDES). Both multilateral and national development banks are usually able to provide credit to companies on terms more

[24] For a detailed survey of national development banks, see: Jose De Luna-Martinez and Carlos Leonardo Vicente, 'Global Survey of Development Banks', *Policy Research Working Paper* (5969; Washington D.C.: World Bank, 2012).

favourable than those of the market, because they can raise funds more cheaply (either direct from public authorities or indirectly by utilising public guarantees of their debt). The development banks differ somewhat in the terms of reference governing the types of projects and sectors to which they can lend. They also usually provide technical assistance to the projects and facilitate dialogue with political institutions.

Public development banks can play an important role in delivering finance to the low-carbon economy, and many of them have already set up specific lending programmes. In the 2007-12 period, at least $425 billion was provided by development banks to projects in renewable energy production, energy efficiency and other environment-related activities (BNEF 2013a). In 2012, investments reached $109 billion, growing 19% from the previous year, contrasting with the negative trend in overall green investment in the same period (see section 1). Among national development banks, KfW has been by far the most active institution, followed by the China Development Bank.

Multilateral development banks – although limited by their smaller budgets compared with the national ones – have been vigorously involved in financing the green economy. During 2011, for instance, the European Investment Bank invested approximately €18 billion, a third of total lending, in activities related to climate change (EIB 2012). The European Bank for Reconstruction and Development since 2006 has invested approximately €10 billion just in the energy sector (EBRD 2012). Multilateral development banks have also been the most active promoters of green bonds.

In the United Kingdom, an even more ambitious experiment has been started through the creation of the Green Investment Bank (GIB), a development bank aimed at helping the country to meet its environmental targets by reducing greenhouse gas emissions, increasing the production of energy from renewable sources, improving energy efficiency and reducing waste (GIB 2013). The GIB was founded in 2012 with an initial allocation of £3 billion capital by the government (now at £3.8 billion), and has since shown a promising capacity to 'crowd in' private investment[25].

The amount of finance made available from national and multilateral development banks is thus far from negligible. However, public development banks have to limit their lending to the amount of finance they are able to raise from government(s) and on the secondary markets through the issuance of bonds. The UK Green Investment Bank has not yet been granted the ability to borrow from the markets. The UK Treasury has frozen this possibility until at least 2015-16 as part of its strategy to reduce the country's public debt relative to GDP. As a consequence, the GIB will not be able to lend in excess of the endowment granted by the government, thus strongly limiting its

[25] In their first five months of operations, the total amount of finance raised by GIB was approximately £2.3 billion, of which £635 million was committed by the GIB itself and the rest by private investors. The average mobilisation ratio was thus around 3:1.

potential to promote the environmental sustainability of the British economic system. Once the £3.8 billion are fully employed, there will be no more money to lend until some previous loan is paid back.

The powers of public development banks must be expanded if they are to play an adequate role in the transition to a low-carbon society. For a variety of reasons – most notably their public component – development banks are the institutions most suited to initiate credit to sectors judged to be socially useful, but the tightness of constraints on their leverage limits the effectiveness of their interventions. A larger role for development banks would help to increase the volume of financial resources flowing to low-carbon sectors, expand the market for green bonds and act as a catalyst for private-sector investors. It would also help to tackle any perceptions that governments were not committed to long-term policies to reduce greenhouse gas emissions.

5. Conclusions

Transitioning to a low-carbon economy will require large macroeconomic adjustments to transform energy systems, improve energy efficiency, alter the built environment and adapt infrastructure. In particular, a financing strategy for the necessary investment is needed if the limit of a 2°C increase in global mean temperatures is to not to be exceeded. Building on simulations using Integrated Assessment Models and on historical evidence, this Report has explored some of the issues posed by this financing challenge.

The first key conclusion is that the financing challenge is not insuperable, given the magnitude of the energy-supply investment flows needed. The LIMITS simulations investigated here suggest that incremental energy-supply investment costs need not be high and indeed may be negative, because of reduced energy demand. Investment in traditional fossil-fuel-based energy supply will also be lower if strong mitigation scenarios are realised. The projections do not, however, take explicit account of the need for more investment in energy efficiency, which are likely to be larger than the incremental investment in energy supply, given the importance of reducing energy use, in particular in buildings and transportation. Incremental GDP costs may also be modest, although, because of higher production (especially energy) costs, higher than incremental investment costs. Incremental costs could be lower still if related market failures and distortions are corrected at the same time as the central market failure due to greenhouse gas emissions (few of these distortions are usually modelled in IAMs). For example, if carbon tax revenues are used in part to reduce distortionary labour taxes and if spending on innovation is raised, GDP is likely to be increased. Further work is needed to assess whether this conclusion about the scale of the financing challenge is robust when a wider range of mitigation actions (such as enhancing carbon sinks) and economic sectors are considered and when investment in improved energy efficiency is explicitly modelled.

Second, historical experience suggests that incremental aggregate investment (and saving) needs are well within the range of historical variation. The clean energy 'investment gap' estimated by McCollum et al. (2014) is of the order of 1% of world GDP, which is smaller than the typical variation through global macroeconomic fluctuations. Several emerging-market economies have experienced in the recent past much larger increases of investment and domestic saving relative to GDP in a short space of time.

Third, government budgets are one feasible financial mechanism to use to meet the financing challenge. Carbon pricing is the key economic tool to bring about climate change mitigation efficiently but requires collective action through public authorities. Use of this tool does not necessarily imply enhanced government revenues. For example, quotas in a cap and trade system to limit greenhouse gas emissions can be given way. But taxing 'bads' such as emissions is an efficient and cost-effective way to raise funds for necessary public spending and some increased public spending is likely to be necessary to implement subsidies to encourage positive externalities from low-carbon innovation. The OECD and World Bank have recommended that countries consider increasing the share of their tax revenues from environmental taxes. Also, the long-term credibility of climate policies would be enhanced if people knew that policy-makers' tax revenues were going to be partly dependent on maintaining the policy framework, while the implications for income distribution and equity of giving away emissions quotas are likely to be more politically unattractive as the value of quotas increases over time.

The LIMITS projections suggest that appropriate carbon pricing would soon generate sufficient fiscal revenues to finance total energy-supply investment, let alone the increment necessary (relative to current policies) to keep below the 2°C ceiling on global temperature increase. The main challenge rather is to ensure that the increased government revenues are used wisely, bearing in mind the size of public sector fiscal deficits and the range of public spending activities. With this in mind, it is important to note that public finance theory points to the disadvantages of formal 'earmarking' or hypothecation of carbon-pricing revenues to particular uses, such as reductions in labour taxes or subsidies to clean energy research or direct public investment in low-carbon energy supply.

Fourth, private finance mechanisms will also be important. The fact that governments are likely to have the capacity to finance the filling of the clean energy investment gap from carbon pricing revenues does not imply that they should do so in full. One of the benefits of carbon pricing is that it incentivises private investment in low-carbon energy supply and increased energy efficiency throughout the economy. Private-sector financing mechanisms suitable for large-scale infrastructure investment have already evolved and can be adapted for many types of low-carbon investment.

However, mechanisms to raise private finance for the low-carbon transition may require the support of policy-makers, for two reasons. The first reason is that the prospective private returns to investment in low-carbon energy supply and energy efficiency improvements are intrinsically dependent on the long-term maintenance of credible and effective climate policies. Much investment in these areas will have to be in long-lived infrastructure, where the costs are upfront but the revenue streams spread over a long time horizon. In these circumstances, political risk and time-inconsistent behaviour by policy-makers are major dangers likely to discourage private investment. Hence it is important that policy-makers find ways of expressing their commitment to the climate-policy regime, for example, through underwriting the political risks, co-investing with the private sector and setting up 'reputational investments' such as statutory underpinning of emission reduction goals.

The second reason is that, at the current economic conjuncture, households and firms in many countries are still deleveraging, attempting to reduce their debts relative to income, despite widespread low real interest rates. Reforms of financial regulation to reduce systemic risk in the global financial system are also likely to make banks less keen to invest in large, risky, long-lived projects. In these circumstances, policy-makers need to build private sector confidence in the future growth of markets for low-carbon energy, goods and services. This can be done in part through direct government spending and in part through broader government behaviour consistent with expectations of meeting climate policy objectives (setting carbon prices, introducing mechanisms to facilitate monitoring of government performance against plans, tackling related market failures in innovation and so forth).

For both reasons, one attractive option is for governments to improve financial intermediation for low-carbon investment by increasing the role of public development banks, in investing directly, in devising new financial instruments to raise funds, in developing technical expertise in investment appraisal and in encouraging co-investment by private investors.

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7. Tables

Table 1 LIMITS Scenarios summary

Scenario	Description	Forcing level target (in 2100)	Before 2020	After 2020	Burden Sharing
Base	No Policy Baseline	/	No policy		/
RefPol	Weak Policy reference case	/	Weak policy		/
StrPol	Stringent Policy reference case	/	Strong policy		/
450	2.8 W/m^2 benchmark case	2.8 W/m^2	2.8 W/m^2		/
500	3.2 W/ m^2 benchmark case	3.2 W/m^2	3.2 W/m^2		/
RefPol-450	Weak policy until 2020 then cooperation to 2.8 W/m^2	2.8 W/m^2	Weak policy	Global GHG tax	/
StrPol-450	Stringent policy until 2020 then cooperation to 2.8 W/m^2	2.8 W/m^2	Strong policy	Global GHG tax	/
RefPol-500	Weak policy until 2020 then cooperation to 3.2 W/m^2	3.2 W/m^2	Weak policy	Global GHG tax	/
StrPol-500	Stringent policy until 2020 then cooperation to 3.2 W/m^2	3.2 W/m^2	Strong policy	Global GHG tax	/
RefPol2030-450	Weak policy until 2030 then cooperation to 3.2 W/m^2	3.2 W/m^2	Weak policy (before 2030)	GLobal GHG tax (after 2030)	/
RefPol-450-PC	Weak policy until 2020 then cooperation to 2.8 W/m^2 with C&C burden sharing	2.8 W/m^2	Weak policy	Global GHG tax	Contraction & Convergence
RefPol-450-EE	Weak policy until 2020 then cooperation to 2.8 W/m^2 with mitigation costs burden sharing	2.8 W/m^2	Weak policy	Global GHG tax	Equal mitigation costs

Table 2 Investment shares and current account balances (1980-2010) Source: IMF(2012)

	Investment share (%GDP)		Current account (%GDP)	
Country Group Name	**Average**	**Stand. dev.**	**Average**	**Stand. dev.**
World	22.87	0.93	/	/
Advanced economies	21.84	1.45	-0.43	0.43
Newly industrialised Asian economies	29.05	3.04	3.98	3.59
Emerging market and developing economies	26.15	1.97	-0.02	2.12
Central and eastern Europe	22.82	2.57	-3.29	2.21
Developing Asia	33.04	3.52	0.57	2.54
Latin America and the Caribbean	21.02	1.80	-1.55	1.70
Middle East and North Africa	24.47	2.00	3.58	7.39
Sub-Saharan Africa	19.09	2.08	-1.80	1.96
Brazil	18.23	2.00	-1.82	2.74
China	40.34	5.13	2.22	3.07
India	26.31	4.95	-1.24	1.08
European Union	21.08	1.39	-0.20	0.67
United States	19.30	1.65	-2.66	1.72

8. Figures

Figure 1 Annual GDP growth rates (upper panel); Per capita GDP (lower panel) – Results from WITCH model

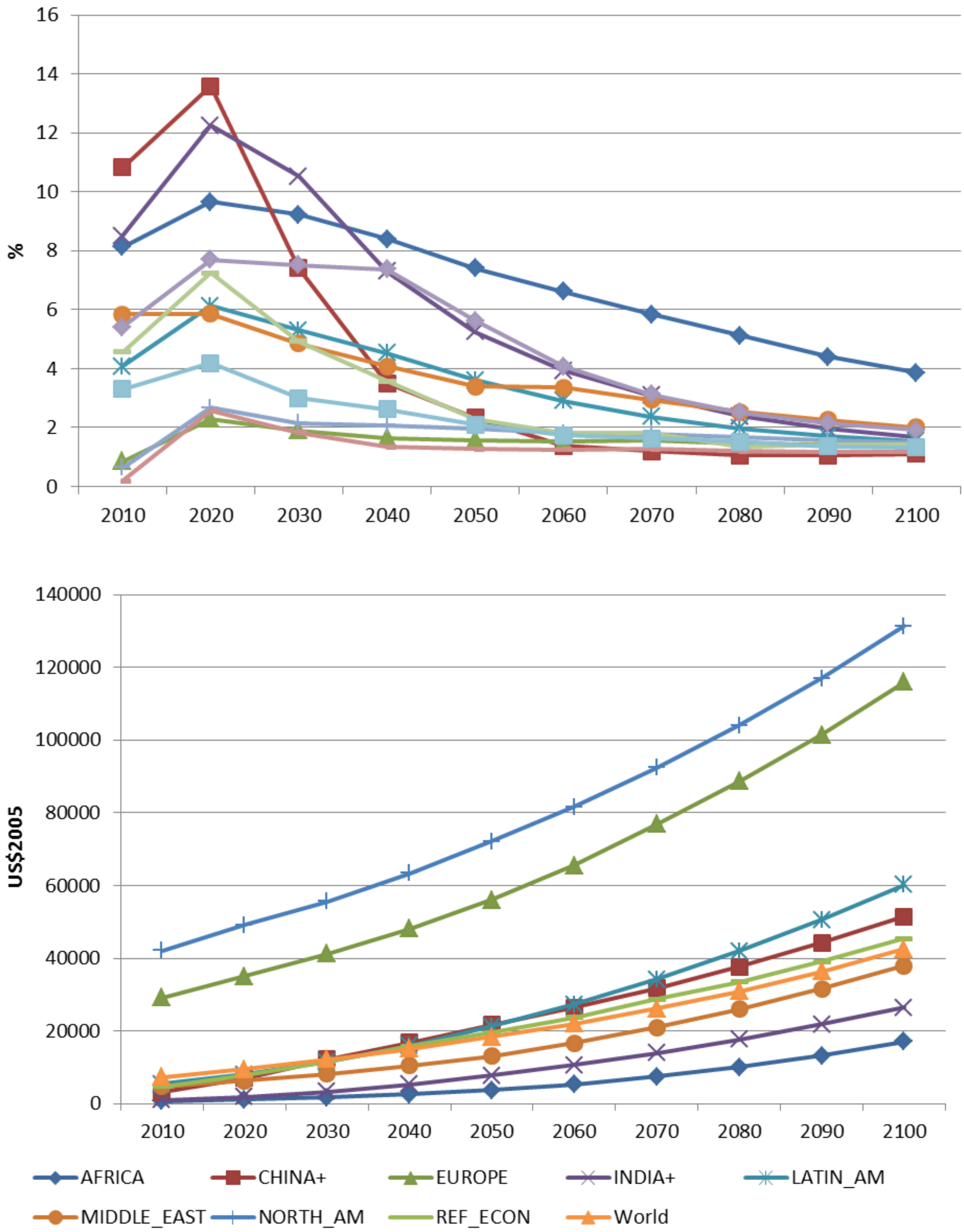


Figure 2 Carbon price dynamics

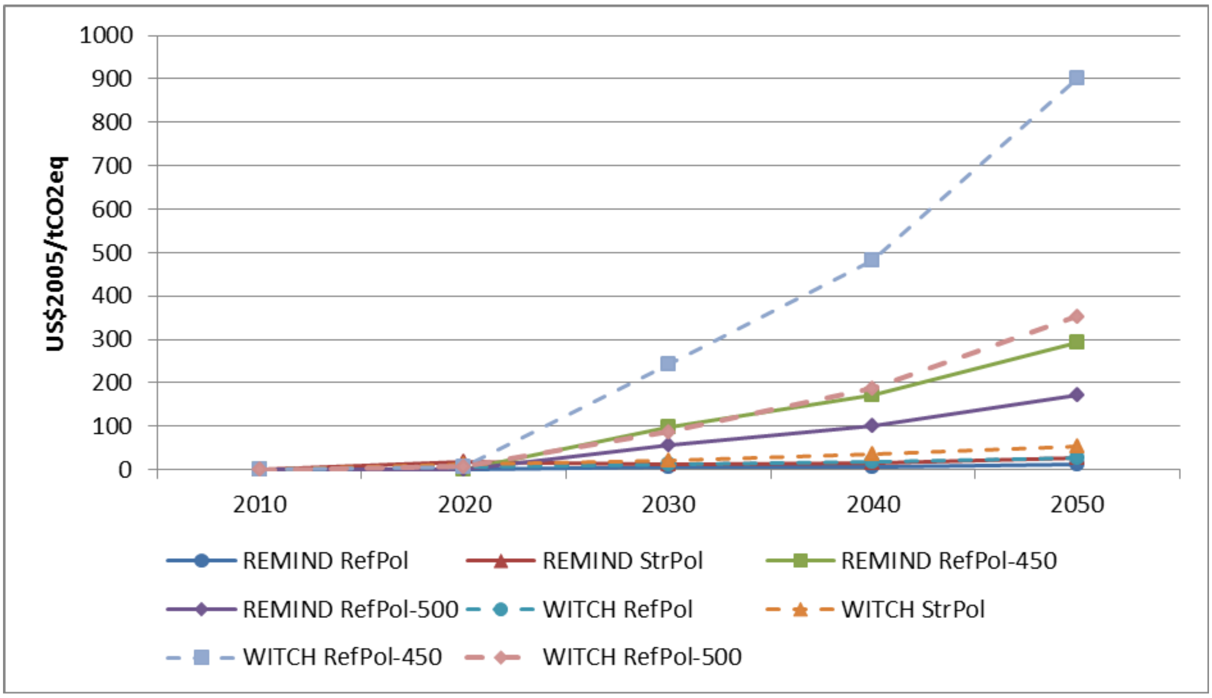


Figure 3 Cumulative investment 2010-50 (difference w.r.t. Base; 5% discount rate)

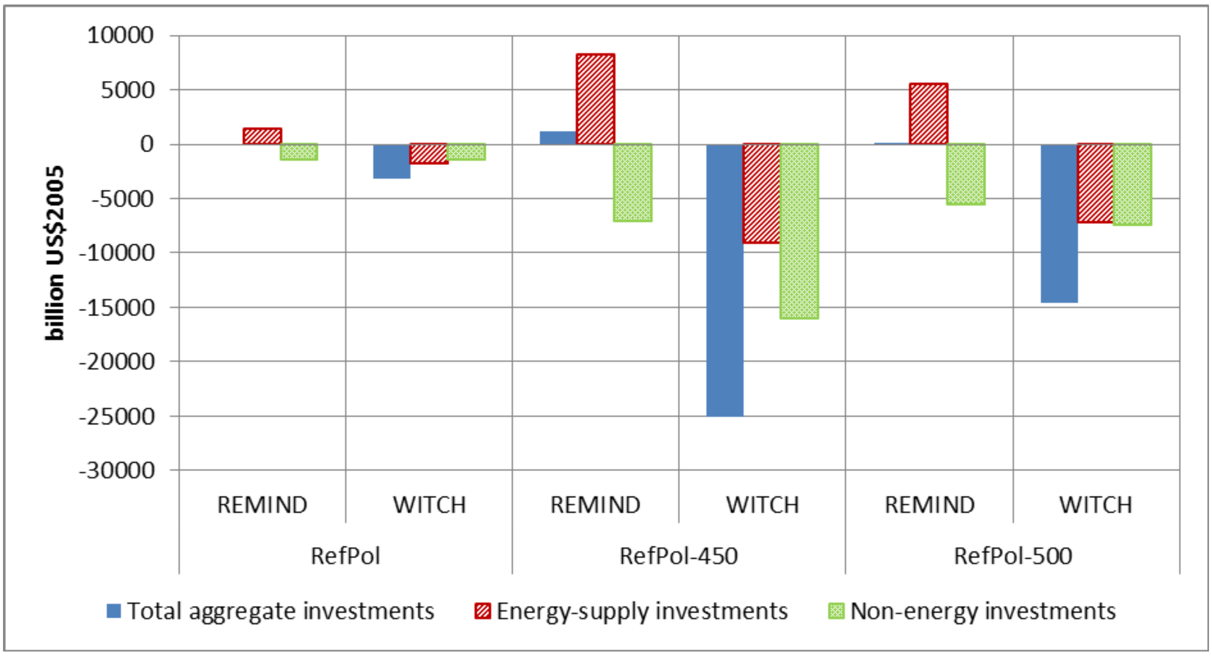


Figure 4 Aggregate investment and macroeconomic costs (cumulative values 2010-50; 5% discount rate)

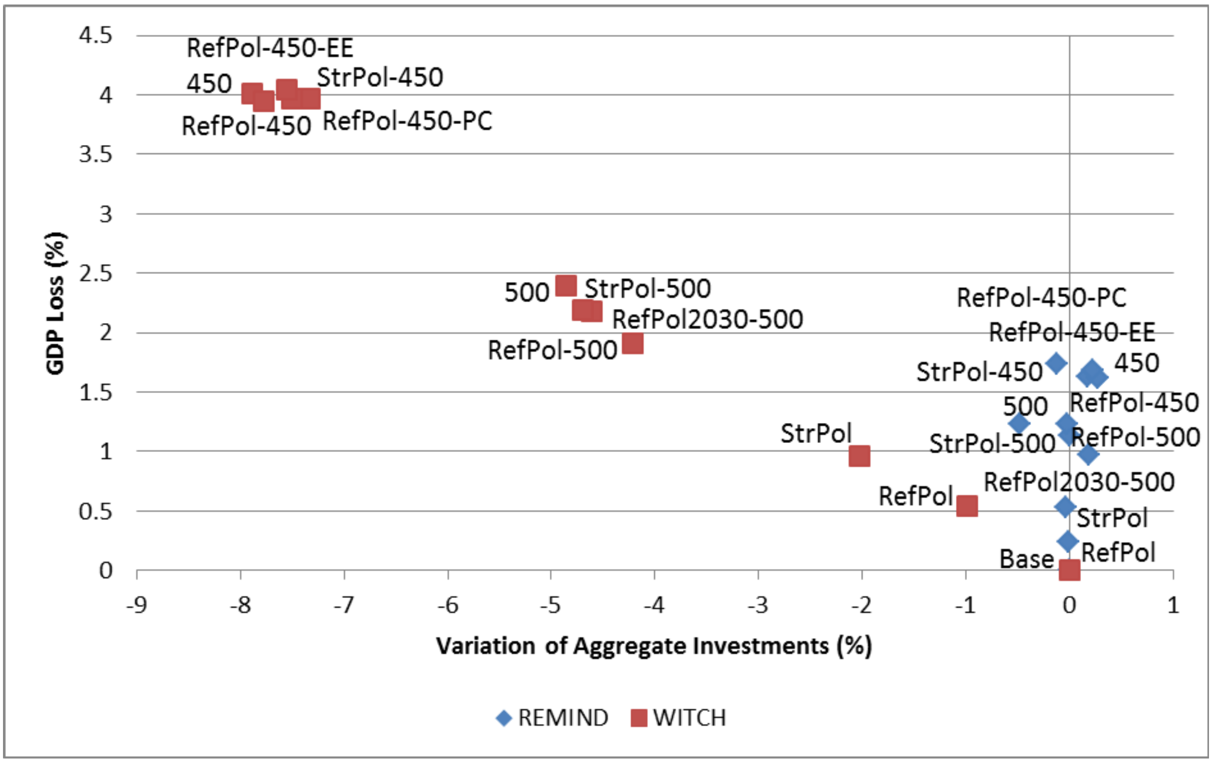


Figure 5 Energy-supply investment and macroeconomic costs (cumulative values 2010-50; 5% discount rate)

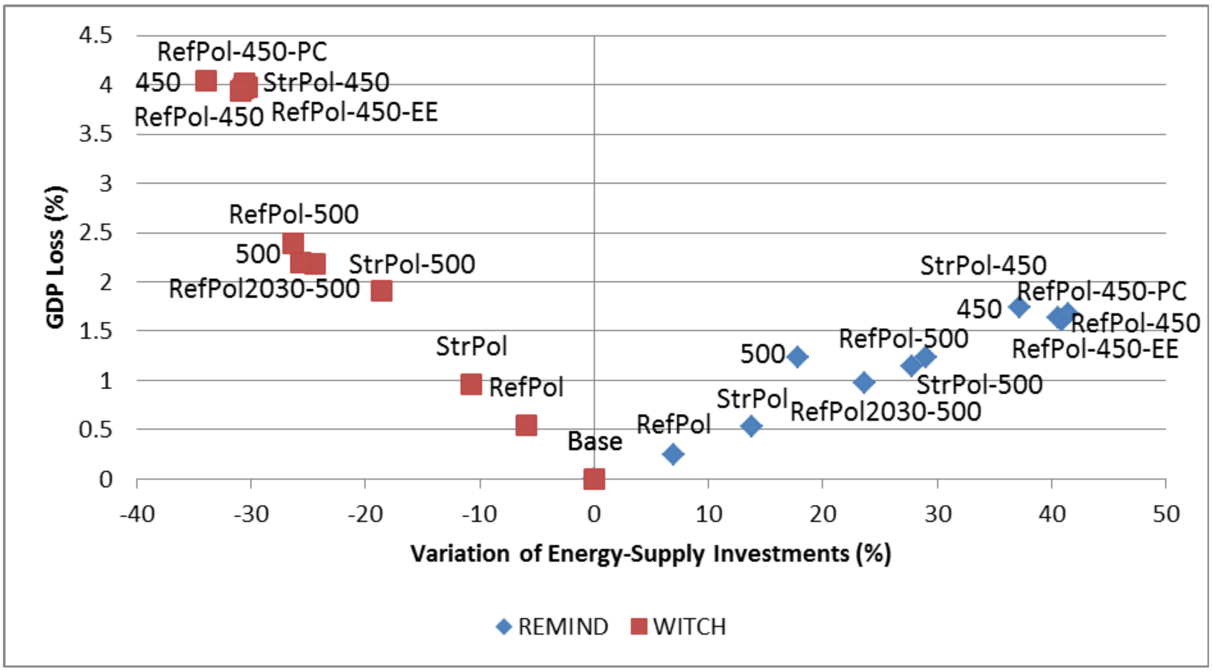


Figure 6 Macroeconomic cost and incremental investment in developing countries for 2020 (upper panel) and 2030 (lower panel)

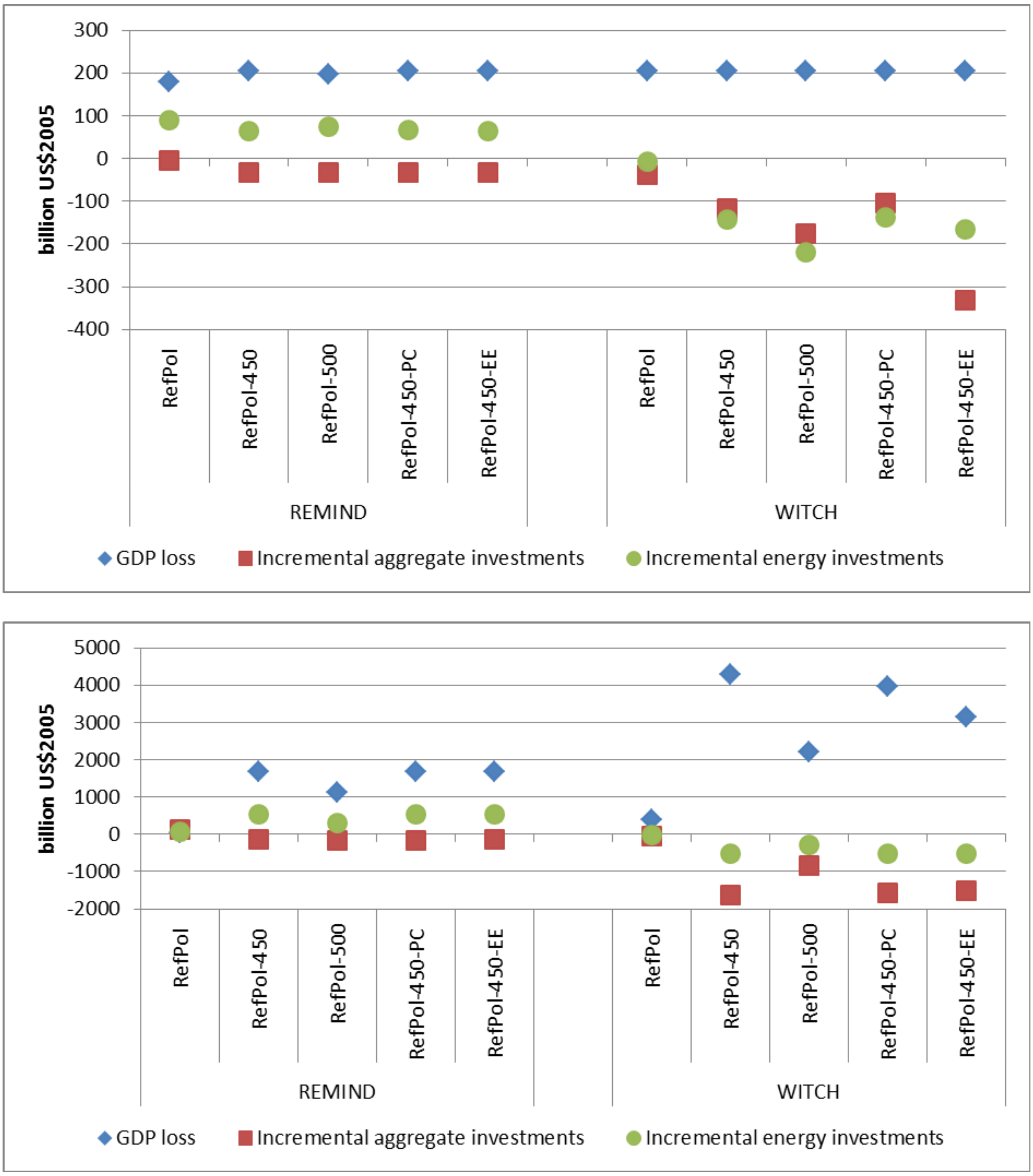


Figure 7 Incremental aggregate investment in RefPol-450 (2010-2050 values)

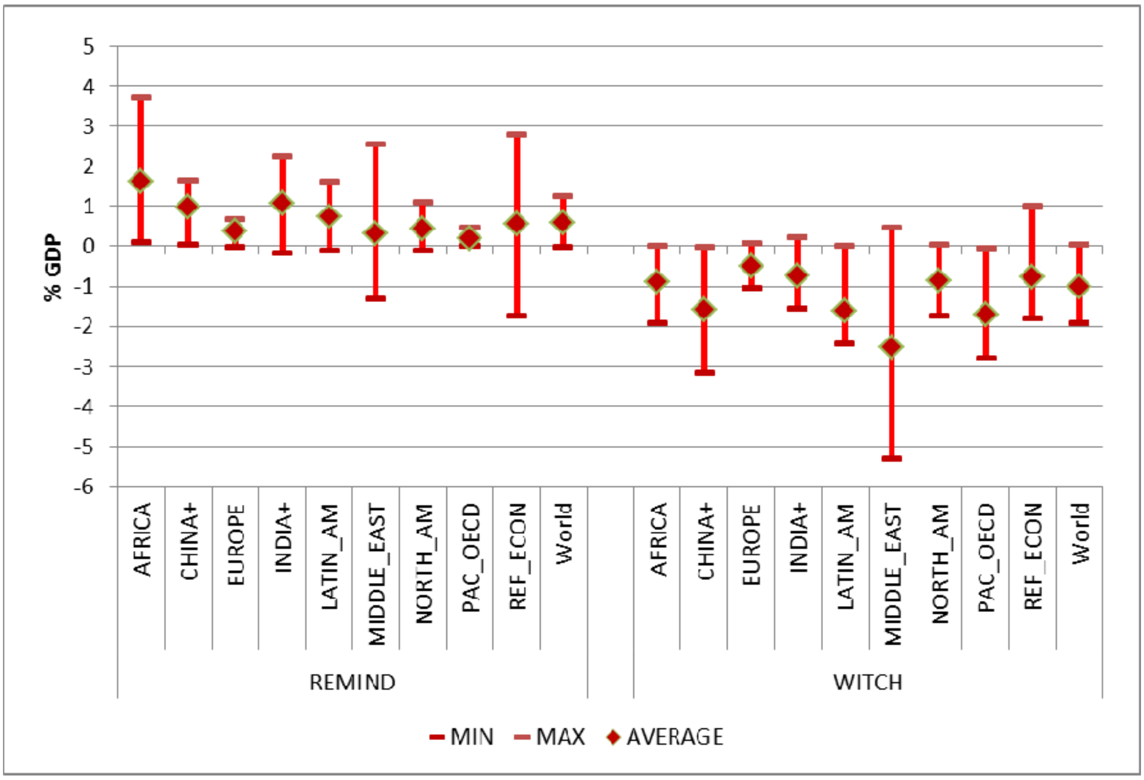


Figure 8 Gross aggregate investment as a proportion of GDP

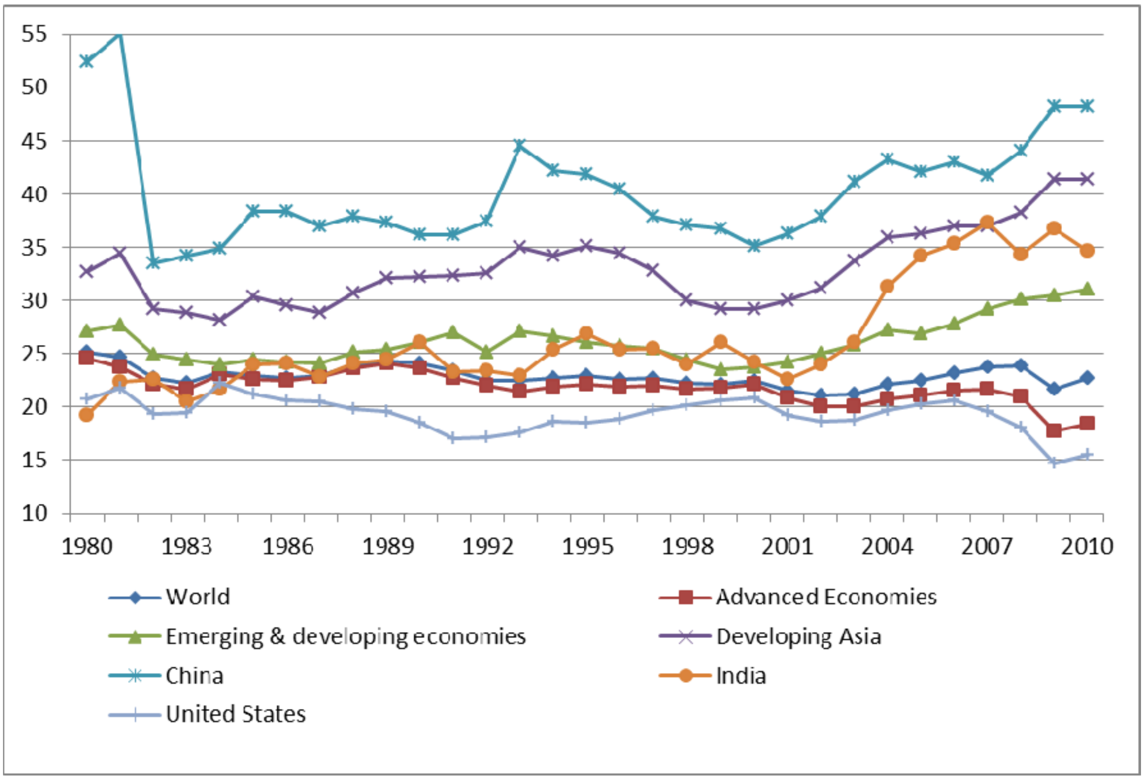


Figure 9 Carbon tax revenues (as share of GDP)

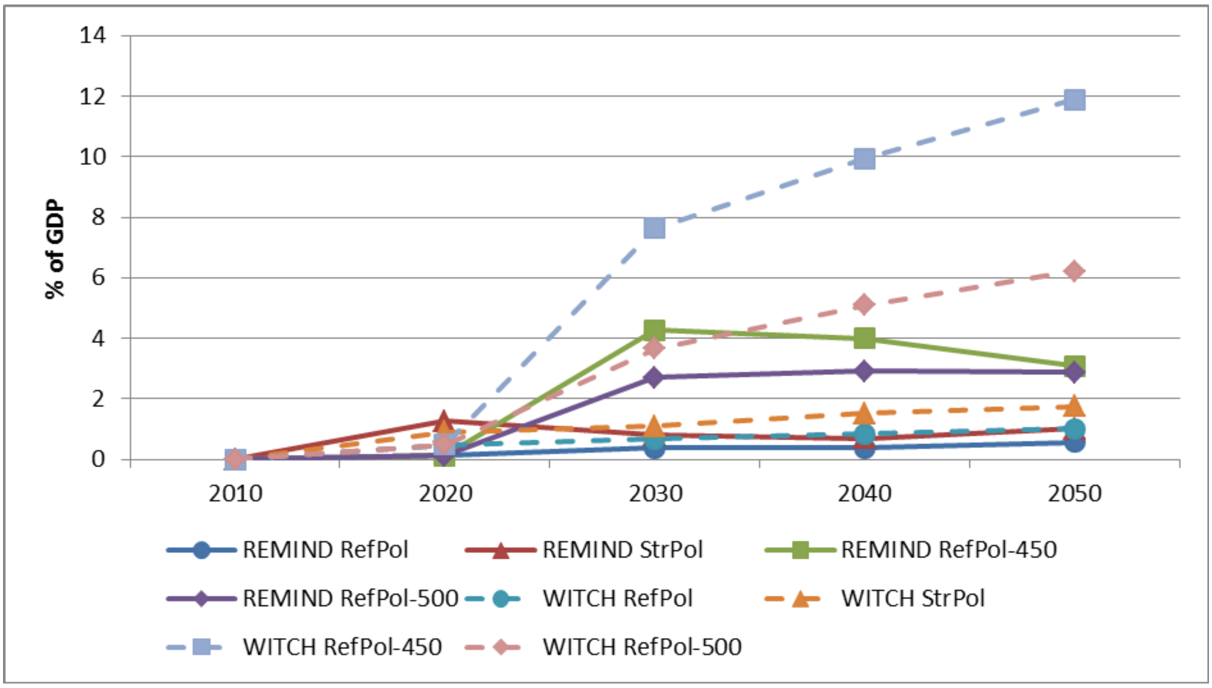


Figure 10 'Fiscal self-reliance' of energy-supply investment (as share of GDP)

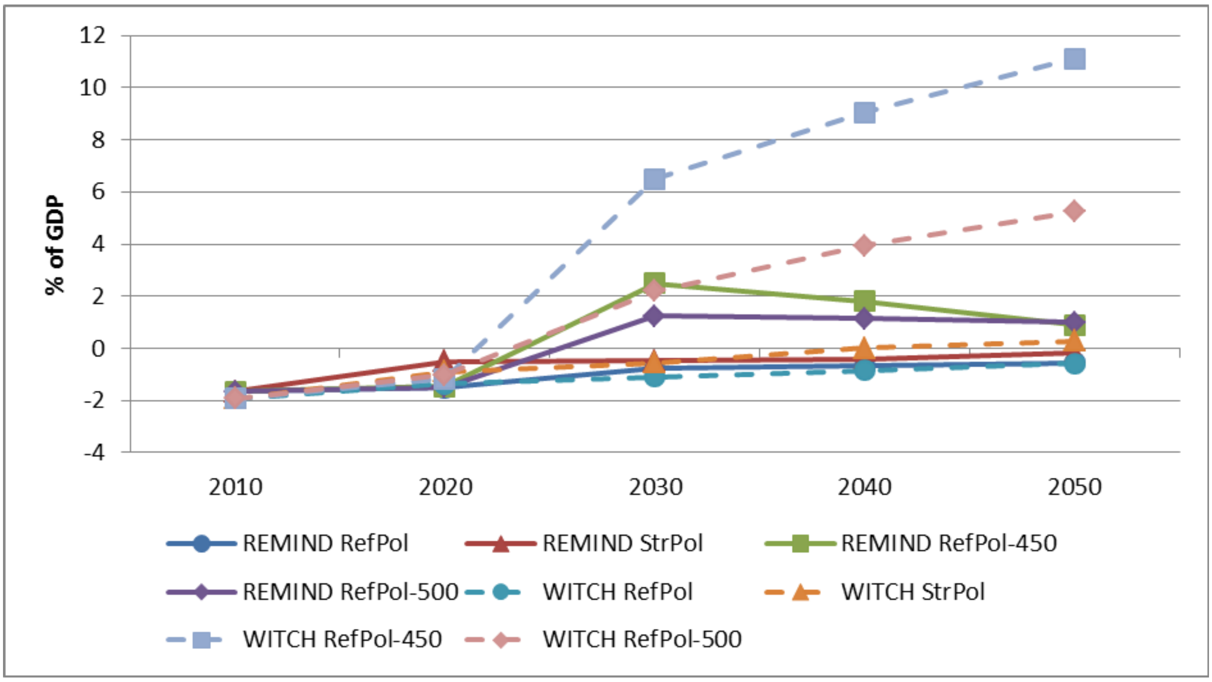


Figure 11 Regional domestic energy-supply 'fiscal self-reliance' for 2030 (REMIND: solid markers on the left; WITCH: dashed markers on the right)

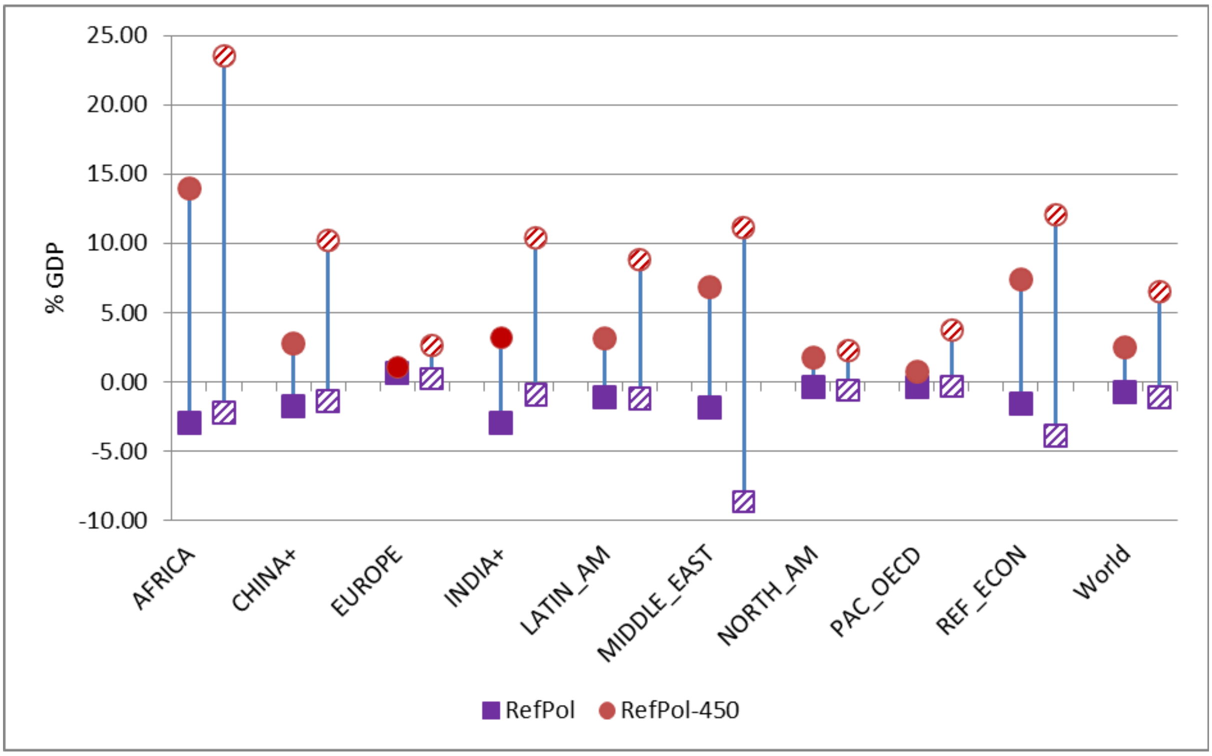


Figure 12 Land use global CO2 emissions (cumulated over 2010-2050 and 2050-2100)

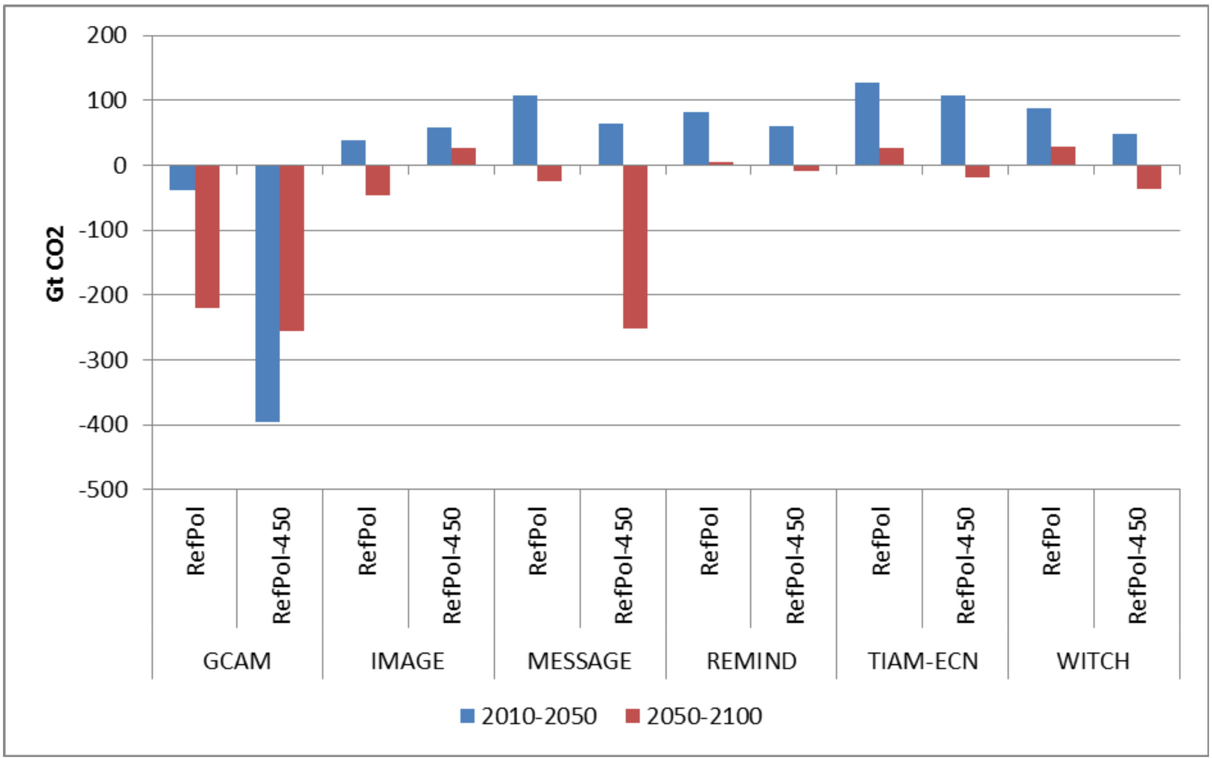


Figure 13 Economic value of CO2 land use emissions (RefPol-450 scenario)

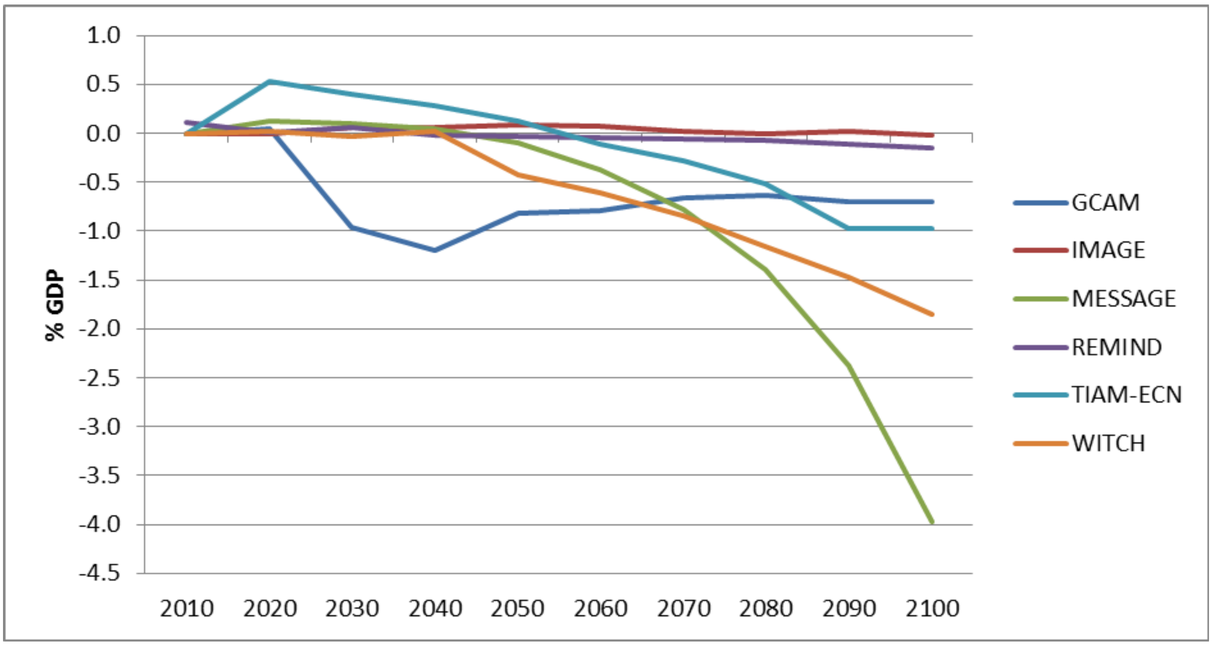


Figure 14 Change in CO2 land use emissions (2010-50 cumulated values, RefPol-450 compared with RefPol)

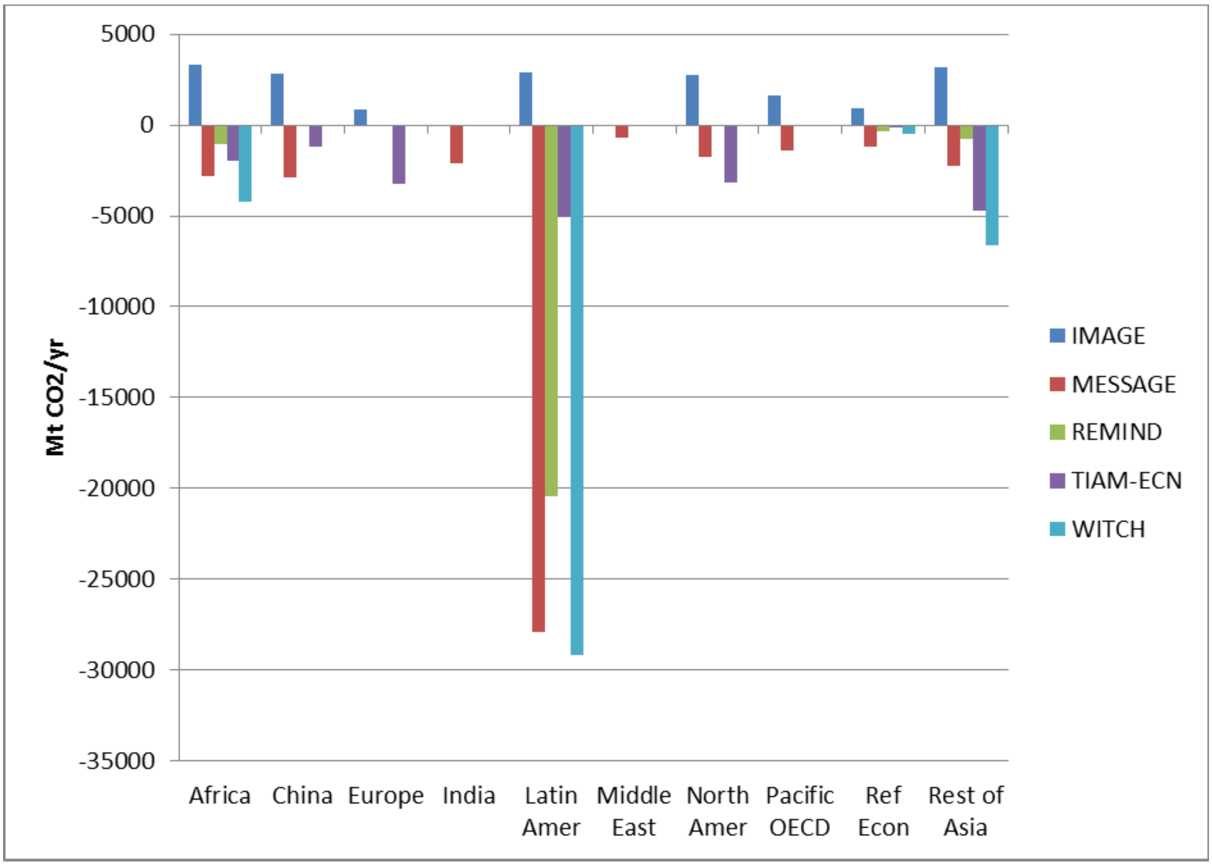


Figure 15 Economic value of land use emissions change (2010-50 cumulated values, RefPol-450 compared to RefPol)

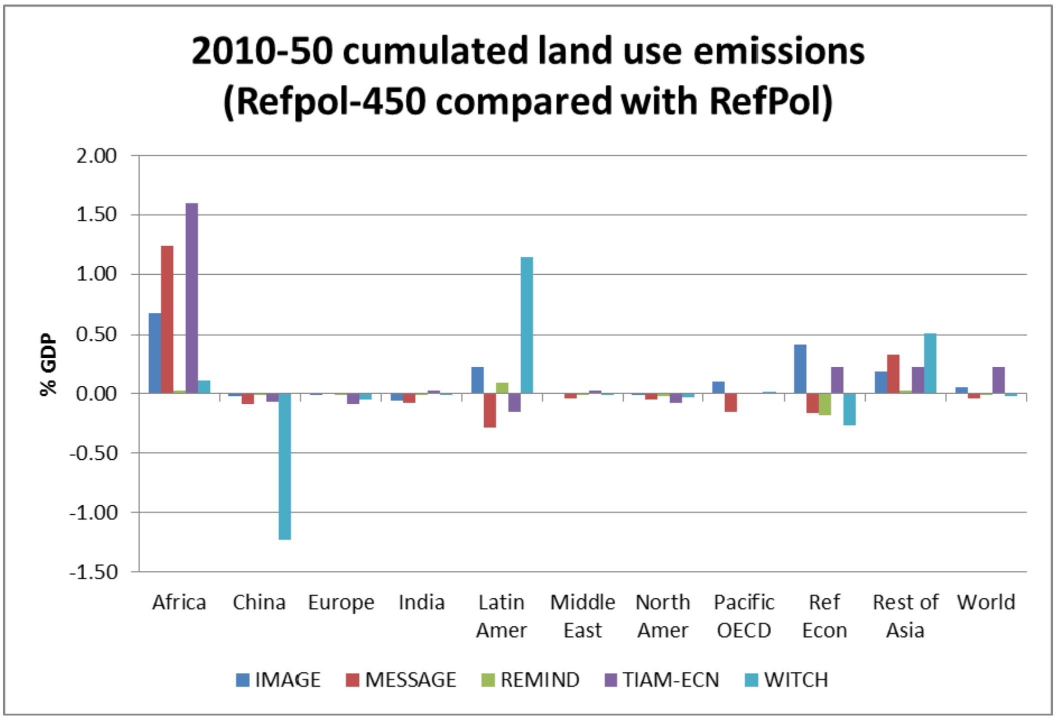
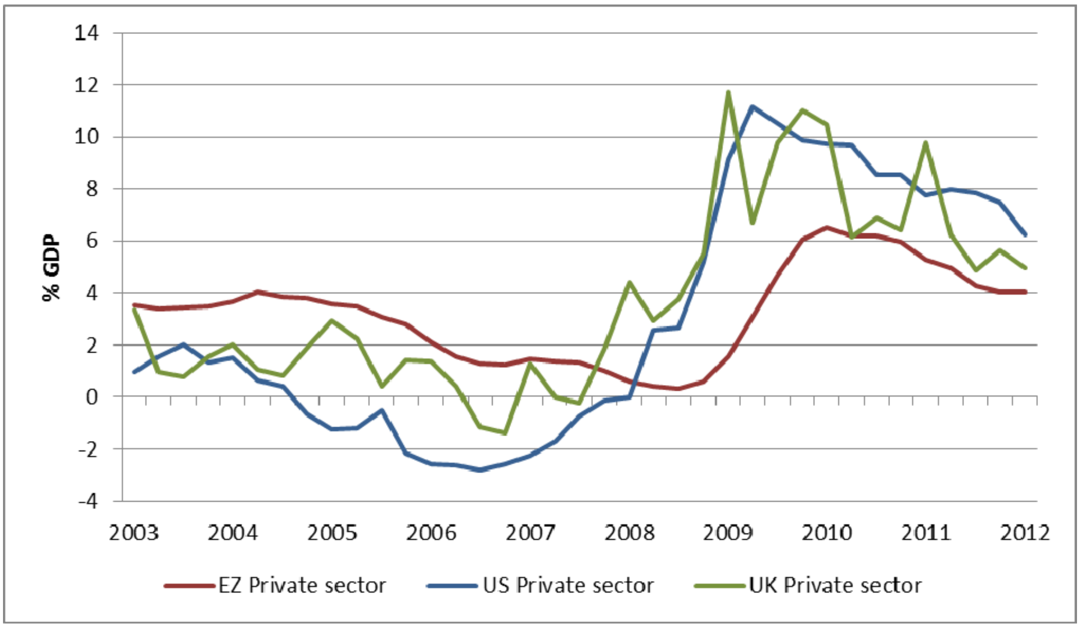
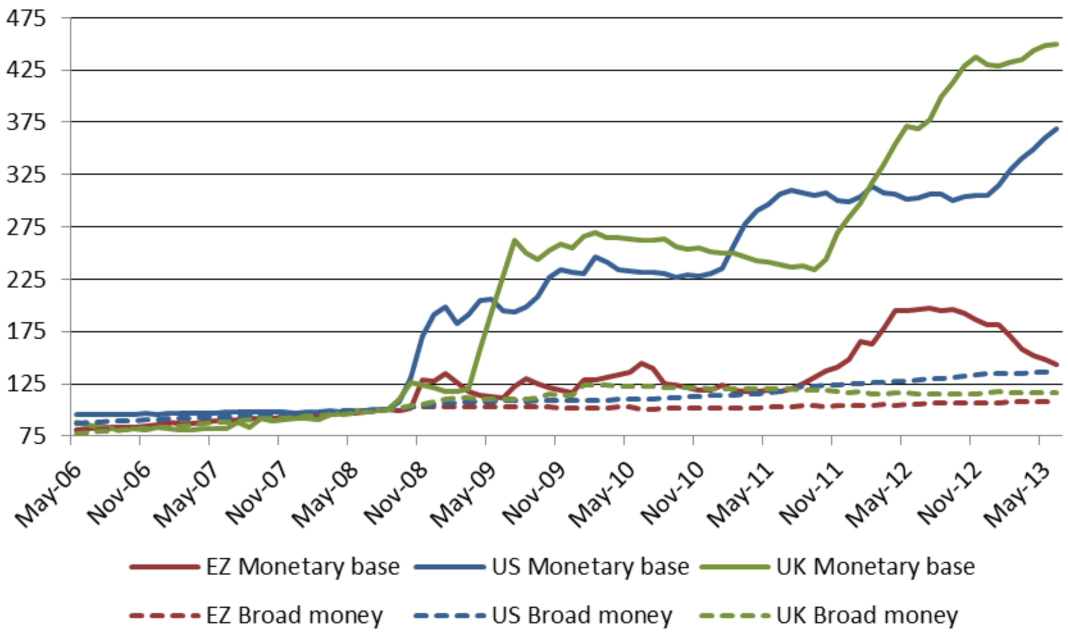


Figure 16 Private sector financial balances in the Euro Zone (EZ), United States (US) and United Kingdom (UK) [26]



[26] The private sector includes households, non-financial corporations and financial institutions. Sources: Eurostat for the euro zone; Bureau of Economic Analysis (BEA) for the US; Office of National Statistics (ONS) for the UK.

Figure 17 Monetary base and broad money in the euro zone (EZ), United States (US) and United Kingdom (UK). August 2008 = 100. [27]



[27] The monetary base is defined as: cash and reserves (UK); monetary base (USA); base money (EZ). Broad money is defined as: M4 (UK); M2 (US); M3 (EZ). Sources: European Central Bank for the euro zone; Federal Reserve Economic Data (FRED) for the US; Bank of England for the UK.