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Sectoral Targets for Developing Countries: Combining "Common but Differentiated Responsibilities" with "Meaningful participation"

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Summary

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Keywords: Sectoral Approach, Sectoral Target

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Sectoral targets for developing countries: Combining "Common but differentiated responsibilities" with "Meaningful participation"

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Abstract

Although a global cap-and-trade system is seen by many researchers as the most cost-efficient solution to reduce greenhouse gas emissions, developing countries governments refuse to enter into such a system in the short term. Hence, many scholars and stakeholders, including the European Commission, have proposed various types of commitments for developing countries that appear less stringent, such as sectoral approaches.

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Keywords

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Introduction

Although a global cap-and-trade system[1] is seen by many researchers as the most cost-efficient solution to reduce greenhouse gas emissions, developing countries governments refuse to enter into such a system in the short term, i.e. in 2013, when the first commitment period of the Kyoto Protocol ends. An option to make developing countries participate could be to grant them a generous allowance allocation, so that they could benefit from participating in the global cap-and-trade system by selling allowances (cf. e.g. Tirole, 2009). However, as we shall see in section 1, this proposal is unlikely to be sufficient to convince developing countries. Moreover it may be refused by developed countries as well since it would imply a massive North-South financial transfer, partly to buy "tropical hot air" (Philibert, 2000).

Hence, many scholars and stakeholders have proposed various types of commitments for developing countries that appear less stringent than the participation in a global cap-and-trade system, such as commitments limited to some sectors. IEA (2009c) as well as Meckling and Chung (2009) provide surveys of these sectoral approaches. Most recently, the European Commission (2009) proposed a "sectoral crediting mechanism" in the run-up to Copenhagen. Surprisingly, very little quantification of these proposals exists. Amatayakul et al. (2008), Amatayakul and Fenhann (2009), as well as Schmidt et al. (2008) assess the amount of emissions that could be reduced through sectoral targets in the main developing countries, but do not assess the economic impact.

In this paper, we assess such a sectoral approach for developing countries. More precisely, we simulate two policy scenarios in which developed countries continue with Kyoto-type absolute commitments, whereas developing countries adopt an emission trading system limited to electricity generation and linked to developed countries cap-and-trade system. We choose the electricity sector for three reasons. First, electricity and heat generation is by far the highest emitting sector: 41% of CO_2 emissions from fuel combustion in 2007, increasing by 60% since 1990 (IEA, 2009a). Second, there will be a massive investment in electricity generation in the next decades: the last World Energy Outlook (IEA, 2009b) projects a growth in electricity demand by 76% from 2007 to 2030, requiring 4 800 GW of capacity additions. Avoiding an irreversible investment in CO_2-intensive capacity, the so-called “carbon lock-in”, is thus of the utmost importance (IEA, 2009c). Third, this sector has a relatively high abatement potential and implementing emission trading is easier there than in sectors with more diffuse sources such as transportation, residential or agriculture.

In one of our two sectoral scenarios, CO_2 allowances are auctioned by the government, which distributes the auctions receipts lump-sum to households. In the other, the receipts are rebated

[1] Or a uniform global tax, which would be equivalent to a global cap and trade system under the assumptions used in the present paper, i.e. no uncertainty (cf. Weitzman, 1974) and no market power on the CO_2 market (cf. Hahn, 1984).

to electricity generation firms as a decrease in pre-existing taxes or a subsidy[2].The economic impact of the latter approach is equivalent to that of an intensity target, which limits the CO_2/MWh ratio, not CO_2 emissions themselves. Both approaches figure in the European Commission sectoral crediting mechanism proposal mentioned above. For a survey of the implications of intensity vs. absolute targets, cf. Quirion (2009).

As we shall see, these scenarios entail a decrease in developing countries CO_2 emissions almost as high as a global cap-and-trade system, for a given abatement level in developed countries and a similar CO_2 price. At the same time, these scenarios may be more acceptable by developing countries governments than a global cap-and-trade system, especially the second one with rebates. Firstly, they are more in line with the principle of "Common but differentiated responsibilities". Secondly, as we shall see, this last scenario entails a much lower increase in the electricity price, thereby limiting the distributional consequences and increasing the acceptability of the climate policy.

To assess these policy scenarios, we use Imaclim-R, a global multi-region, multi-sector general equilibrium model designed to assess CO_2 emissions scenarios and policies. Imaclim-R is a hybrid model of a second-best world economy: it represents in a consistent framework the macro-economic and technical world evolutions, taking into account second-best features such as possible underutilization of production factors (labour and capital) and imperfect anticipations. The model is fully detailed in Sassi et al. (2010) and tested against real data in Guivarch et al. (2009).

The structure of the article is straightforward. Part 1 details the reasons why a worldwide emission caps scheme is unlikely. The scenarios are described in part 2, the results presented in part 3 and a fourth part concludes. Appendix 1 provides a description of the Imaclim-R model and Appendix 2 the results concerning the world energy prices.

1. Why a global emission cap is unlikely, but abatement in developing countries necessary

At least four factors explain why developing countries governments are reluctant to participate in a global cap-and-trade system.

Firstly, the principle of "common but differentiated responsibilities", laid down in article 4 of the UNFCCC, implies that developed countries should implement abatement policies and measures sooner than developing countries. Imposing the same nature of obligations in developed and developing countries may thus be seen as a violation of this principle. Admittedly, it can be defended that a global cap-and-trade system with more stringent targets

[2] Since a single sector is covered, reducing taxes on labour or on production yields the same result so far as we make the simplifying assumption that the labour/output ratio is the same across electricity production technologies. Otherwise, reducing taxes on labour would increase the share of labour-intensive options. If several sectors were covered, a uniform reduction in labour taxes would again favour labour-intensive sectors.

in developed than in developing countries fits with this principle, but the opposite view seems prevalent in developing countries.

Secondly, absolute emissions caps are often viewed as a constraint to economic growth and to the right to (sustainable) development, which is also acknowledged by the UNFCCC in its article 3. Certainly, this reasoning is doubtful since it neglects both the possibility to decouple emissions from economic growth and the access to the global carbon market. Yet, here again, this view is widespread among developing countries governments.

Thirdly, a global cap-and-trade system is the most cost-efficient solution only if the global CO_2 price is not limited to inter-governmental emission trading, but is decentralised in the form of an emissions tax or of a domestic emission trading system in all countries. Although cost-effective, such policies would have large distributional consequences in developing countries and the increases in the energy costs caused by the CO_2 price may well trigger strong political protests.

Fourthly, some analysts (e.g. Strand, 2009) underline the “revenue management” issues in case of a large transfer of emissions allowances, including the so-called “Dutch disease”, i.e. the decrease in industry competitiveness entailed by the real exchange rate appreciation caused by the transfer.

For all these reasons, the prospect of a global cap-and-trade system is extremely unlikely at least in the short run. Indeed, one can fear that developing countries participation in a global climate agreement – in the event of such an agreement – will be very weak. In most proposals currently on the negotiating table (WRI, 2009a), including the recent Copenhagen Accord (UNFCCC, 2009), this participation takes the form of a list of mitigation actions, that is a list of heterogeneous policy measures whose additionality would be difficult or even impossible to assess, and which would be far from cost efficiency.

Moreover, in spite of the recent political changes in the United States, and as we could see during the Copenhagen negotiations, the US administration and Senate still insist on a meaningful participation of major developing economies. Indeed, without a rapid decarbonisation of the major developing countries, limiting global warming to 2°C over the pre-industrial level is out of reach: in 2005, non-Annex I parties Greenhouse gas emissions (including the six Kyoto gases, international bunkers and emissions from land-use change and forestry) amounted to 56% of the global total and this share is increasing (WRI, 2009b).

2. Scenarios

We simulate five scenarios, among which the first three are benchmarks to which the latter two can be compared. We deliberately chose to simulate very simple architectures: the aim is indeed to shed light on the economic mechanisms and not to assess fully realistic designs.

In every scenario but the business-as-usual one, Annex I countries[3] as a whole have the same emissions, and the scenarios differ by the climate policy implemented (or not) in developing countries. Note that the international CO_2 price resulting from these policies is almost equal across scenarios (cf. Figure 14 in Appendix 2). Hence, had we compared scenarios for a given CO_2 price rather than for a given emissions level in Annex I, we would have had similar results.

BAU. This is a business-as-usual scenario, i.e. without any climate policy. Since our focus is on comparing the scenarios rather than on forecasting emissions, in this scenario as well as in the others, we neglect the climate policies that have been or will be implemented before 2013. CO_2 emissions from fossil fuel combustion increase from 24 Gt in 2001 to 33 in 2013 and 37 in 2030.

Global_Cap. A global cap-and-trade system is implemented from 2013 on. A trajectory of CO_2 emissions caps is prescribed from 2013 on in order to limit the CO_2 concentration at 450 ppm (excluding emissions from land-use, land-use change and forestry). Emissions peak at 34 Gt in 2015 and then decrease to 25 Gt in 2030. This global emission cap is split among the regions according to a "contraction-and-convergence" approach, with a convergence of per capita allowances in 2100 and a linear progression towards this target from 2013 to 2100. The regions then trade allowances with each other at a single world CO_2 price. This inter-region cap-and-trade system is decentralised through domestic emission trading systems covering all CO_2 emissions from fossil fuel combustion, so that every emission source pays the same CO_2 price in every sector and in every region.

All allowances are auctioned, but the use of receipts differs across sectors. In all productive sectors except electricity generation, auction receipts are distributed to firms as a decrease in the pre-existing production taxes, or (when the auction receipt are higher than the amount of the production tax) as a subsidy. Auction receipts of the allowances which cover emissions from households and electricity producers are distributed to households as a lump-sum. This hybrid way of using the auctions revenue is consistent with the functioning of the European Union Emissions Trading System (EU ETS) from 2013 on: electricity generation will have to buy allowances at auctions and the receipts will go to the general public budget, while the large majority of other sources will receive allowances free of charge. For industry, the quantity of allowances an installation receives under the EU ETS is roughly proportional to its production capacity (Ellerman, 2006). Over the long run, the production level and the production capacity are almost proportional, so this way of allocating allowances is roughly equivalent to a subsidy on production.

[3] Throughout the text, we use the terms "Annex I countries" and "developed countries" indifferently, as well as "Non-Annex I countries" and "developing countries".

Annex_I_Only. Annex I countries have the same emissions as in the Global_Cap scenario and also trade allowances with each other. The difference is that no climate policy is implemented in developing countries.

Elec_Households. Annex I countries have the same emissions as in the Global_Cap and Annex_I_Only scenarios and also trade allowances with each other. Developing countries implement an emission trading system limited to electricity generation, linked to developed countries cap-and-trade system. We set the amount of allowances allocated in each developing country electricity sector so that it equals its ex post emissions at the CO_2 price defined by the Annex I CO_2 market. In other words, developing countries are neither sellers nor buyers on the global CO_2 market[4]. This sectoral target is decentralised through a domestic emission trading system, with domestic allowances auctioned by developing countries governments, who distribute the auctions revenues as a lump-sum to households.

Elec_Rebates. The only difference with the previous scenario is that in developing countries, auction receipts are distributed to electricity generation firms as a decrease of the pre-existing production tax or as a production subsidy.

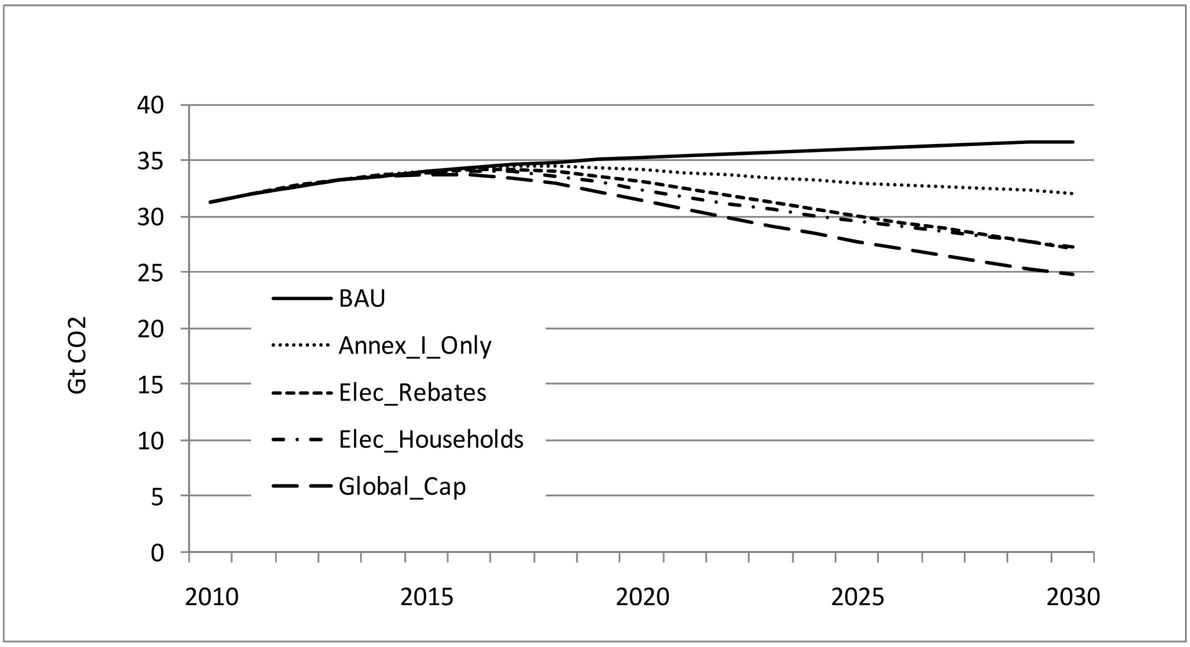
3. Results

3.1. CO_2 emissions: the sectoral approaches provide almost as much abatement as the global cap-and-trade system

Obviously, the global emission trajectory is the highest in the BAU scenario and the lowest in Global_Cap (Figure 1). In the Annex_I_Only scenario, the emission trajectory is closer to BAU than to Global_Cap, for two reasons. First, imposing a cap on Annex I emissions only deals with around half of the issue, since in our BAU scenario these countries emit 50% of the emissions cumulated over 2013-2030. Second, a part of the abatement in developed countries "leaks" to developing countries, as is apparent in Figure 3 below. This leakage is very limited: the leakage-to-reduction ratio is only 8% in 2030. It comes mainly through two mechanisms. First, the world prices of oil, coal and natural gas are reduced by CO_2 abatement measures in developed countries (cf. Figure 11-13 in Appendix 2), thereby increasing emissions in developing countries. Second, the competitiveness of the energy-intensive industries of developed countries is reduced by the climate policy, leading to a loss in market shares to the benefit of developing countries producers, whose emissions increase.

[4] Admittedly, in the sectoral crediting mechanism proposed by the European Commission (2009) and in most other proposals, the crediting target would be set at a higher level than expected emissions, so that developing countries would benefit from a transfer of CO_2 allowances from developed countries. We did not include such transfers in order to disentangle the impact of transfers from the other economic mechanisms.

Figure 1. Global CO_2 emissions



The most interesting point in Figure 1 is that in the two sectoral scenarios, emissions are much closer to Global_Cap than to Annex_I_Only. Indeed in 2030, global abatement compared to the BAU scenario reaches 32% in Global_Cap, 26% under the two sectoral scenarios and only 13% under Annex_I_Only. In other words, in 2030, both sectoral scenarios reach 80% of the abatement (compared to BAU) of Global_Cap. Two factors explain this positive result. First, electricity generation is the main emitting sector in the BAU scenario, with 41% of emissions in 2030. Second, this sector benefits from relatively cheap abatement possibilities, especially compared with transportation. In this regard, Imaclim-R converges with the 19 models compared by Clapp et al. (2009).

Figure 2. Annex I CO_2 emissions

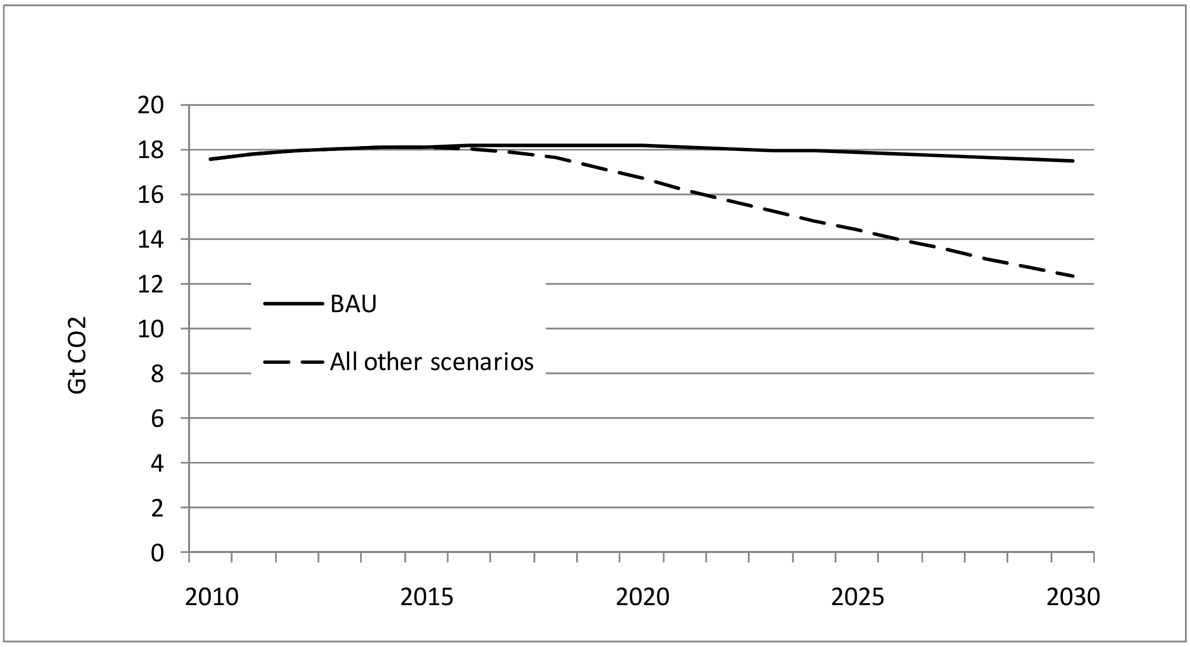


Figure 3. Non-Annex I CO_2 emissions

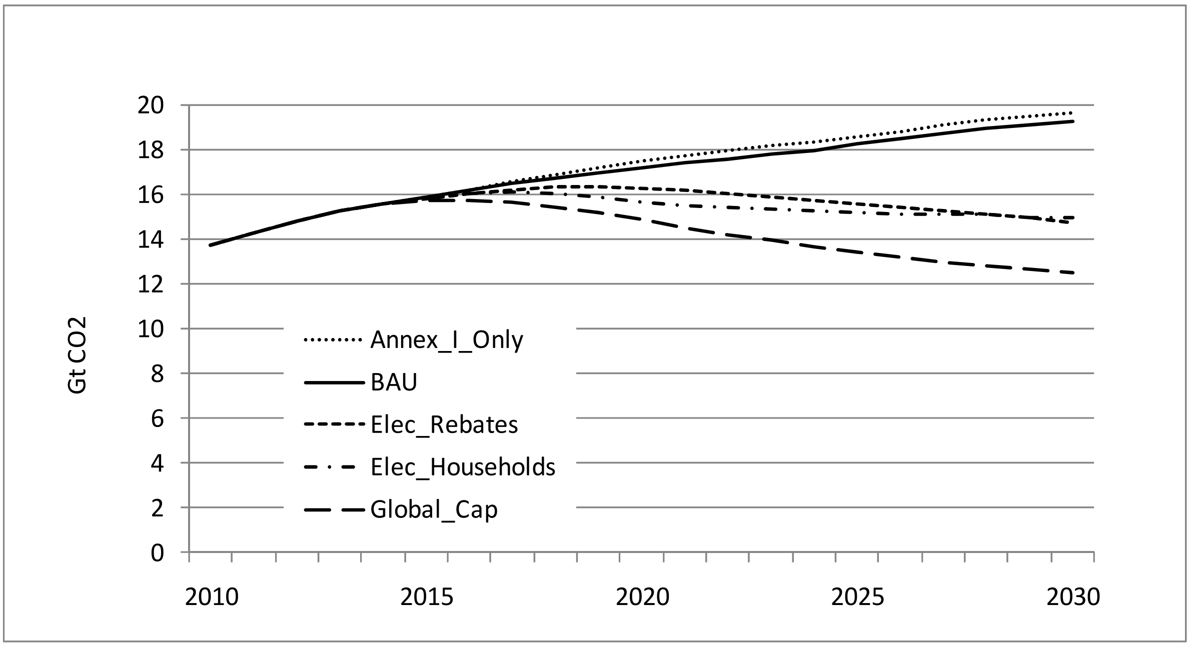
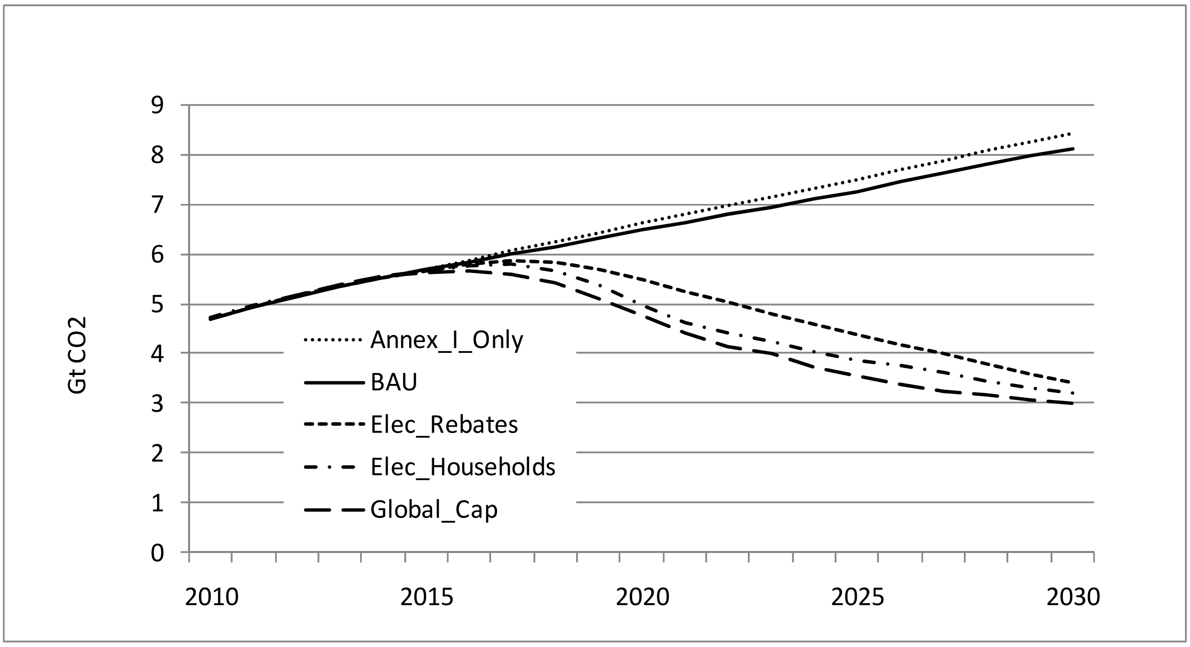


Figure 4 focuses on emissions from electricity generation in non-Annex I countries. In both sectoral scenarios, emissions are close to Global_Cap but a little higher. In Global_Cap, electricity consumption is reduced since the overall economic activity is more impacted by the climate policy (cf. Figure 6 below). Emissions are slightly higher in Elec_Rebates than in Elec_Households. Indeed, in the former scenario, the rebate partially offsets the price increase, hence electricity generation is less impacted and the decrease in emissions is lower.

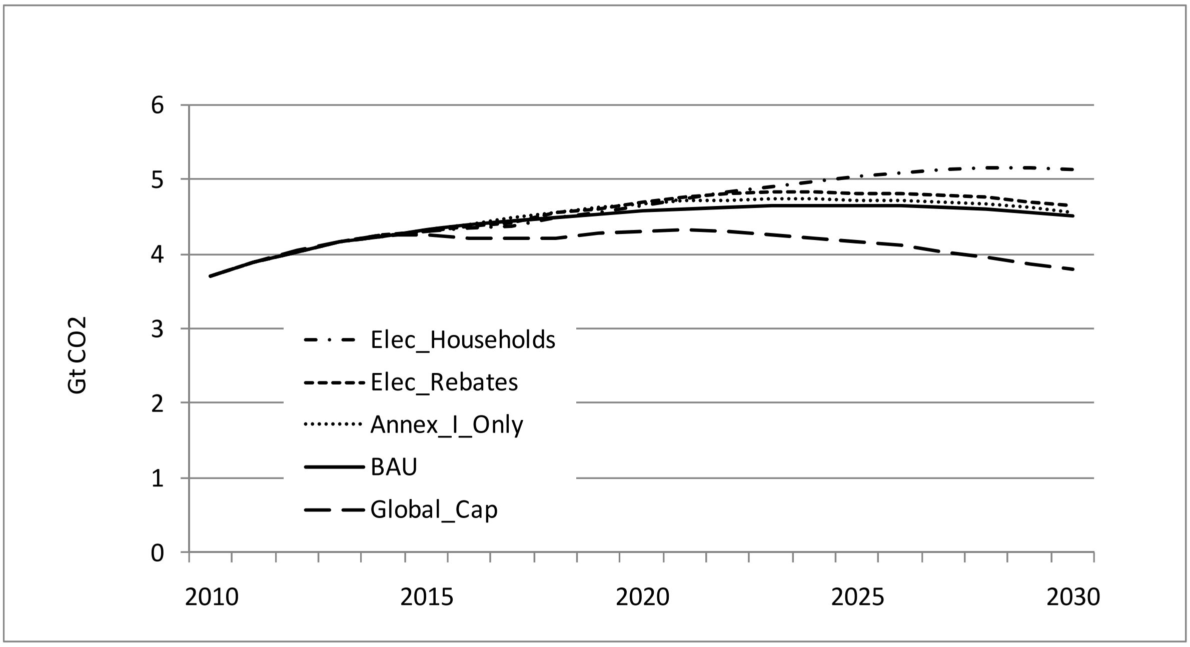
Figure 4. Emissions from power generation in non-Annex I countries



In Elec_Households and, to a much lesser extent, in Elec_Rebates, emissions from the energy-intensive industry in developing countries actually increase compared to BAU (cf. Figure 5). This is because the rise in electricity price (cf. section 3.3 below) induces industry to substitute fossil fuels for electricity. In other words, there is an inter-sectoral emission leakage, which explains why, in 2030, aggregate non-Annex I emissions are a little lower in Elec_Rebates than in Elec_Households (Figure 3) although non-Annex I emissions from power generation remain higher in Elec_Rebates than in Elec_Households over all the simulation period.

As shown in Figure 5, in Annex_I_Only, emissions from the energy-intensive industry in non-Annex I countries are a little higher than in BAU, because developing countries CO_2-intensive industries win market shares vis-à-vis developed countries, generating a small amount of carbon leakage.

Figure 5. Emissions from the energy-intensive industry in non-Annex I countries



3.2. GDP losses: The sectoral approach with rebates entails much lower GDP losses in developing countries

As is apparent from Figure 6, the transitory GDP losses in developing countries are significant: they reach more than 3% (compared to BAU) around 2018. After that, GDP progressively catches up with its BAU level. This partial catch-up is due to induced technological change mechanisms (Crassous et al., 2006) and less vulnerability to peak oil. The economies vulnerability to peak oil in baseline scenarios is due to the imperfect expectation of oil price increase when producers are constraint by depletion of resources. This imperfect expectation is partially corrected by carbon pricing: technical change and consumption structure change induced by climate policies reduce economies dependence on oil. Nevertheless the prospect of such short term losses would be difficult to accept for developing countries governments. In Elec_Households, the losses are lower but still reach 2% around 2018. Note that in this scenario, GDP is actually higher than in BAU after 2029, mainly because developing countries benefit from lower world energy prices. In Elec_Rebates, GDP losses are always less than 1% and GDP is higher than BAU as soon as 2020.

From Figures 3 and 6, we can see that in the late 2020s, Elec_Rebates provides a similar emissions reduction than Elec_Households for a much lower impact on GDP in developing countries. This result may surprise since in a simple model without pre-existing distortion and without leakage, using the auction or tax receipts as a production subsidy increases the abatement cost, for a given abatement target (e.g. Fischer, 2001), compared to a lump-sum distribution of the receipts. The explanation is that in our setting, a lump-sum distribution of the receipts exacerbates the pre-existing distortions and generates inter-sectoral emissions leakage (from electricity generation to industry) more than a distribution of the receipts as a decrease in pre-existing production taxes or as a production subsidy.

Finally, in the Annex_I_Only scenario, developing countries GDP increases compared to BAU for two reasons: they win some market shares in CO_2-intensive goods vis-à-vis Annex I regions and they benefit from lower world energy prices.

GDP losses in China follow the same trends, but with higher magnitudes (Figure 7), because of its high CO_2-intensity: 0.6 kg CO2/US$ PPP in 2007 vs. 0.47 for the world average and 0.48 for non-Annex I countries in average (IEA, 2009a).

Figure 6. GDP losses in non-Annex I countries

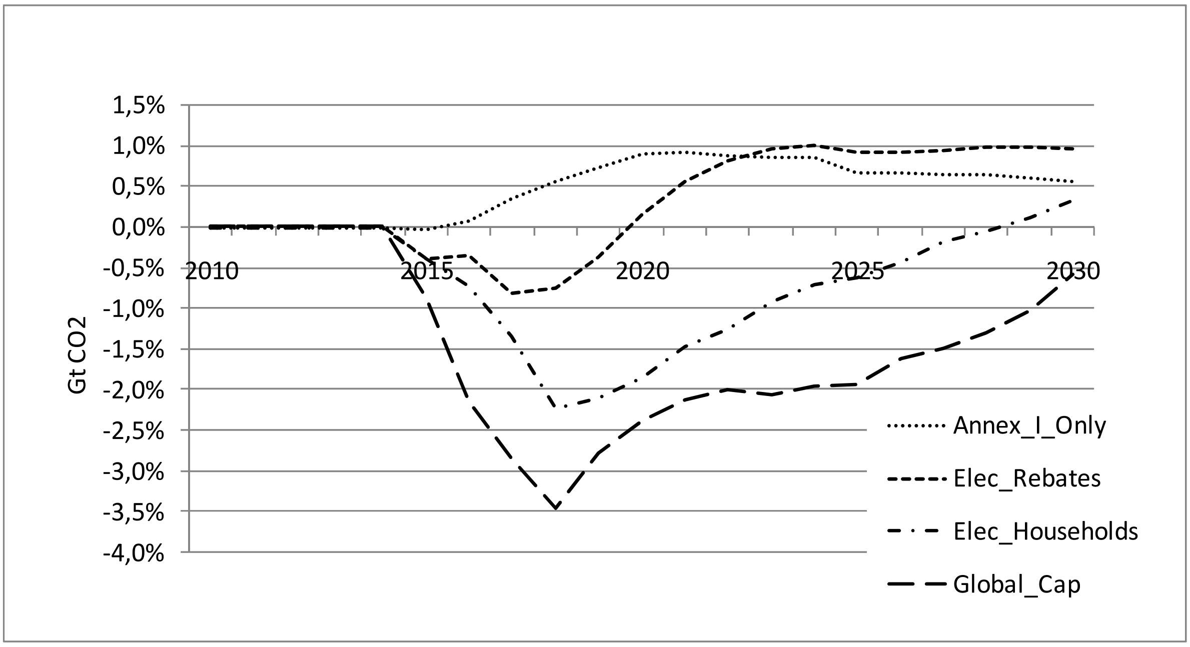
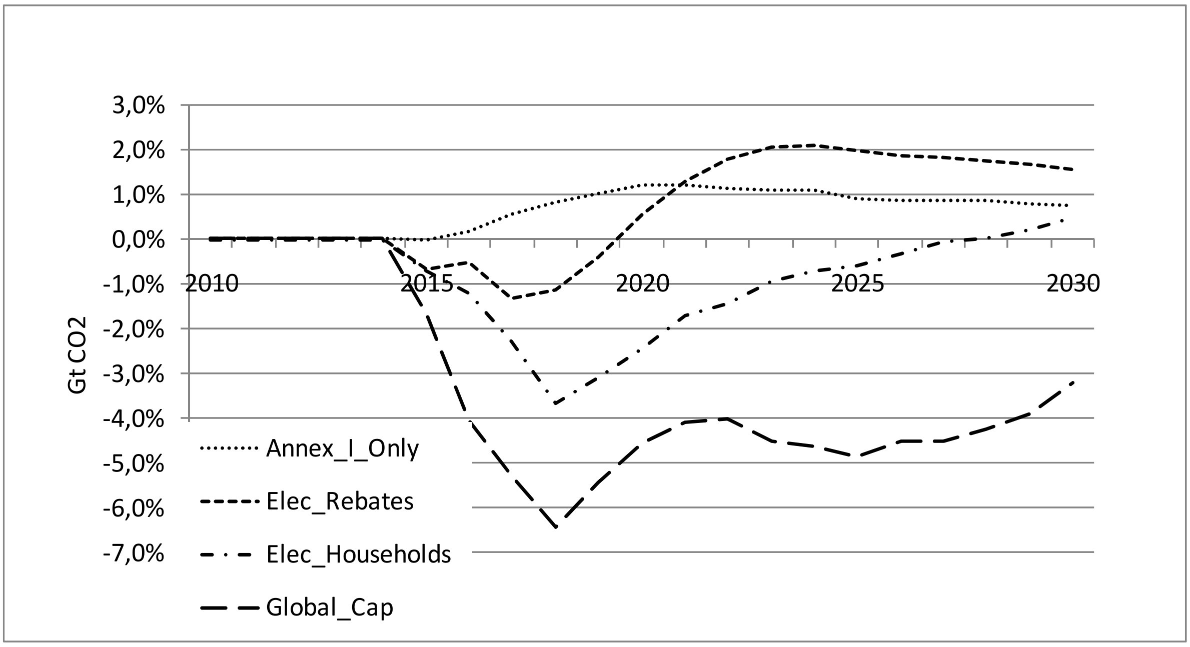
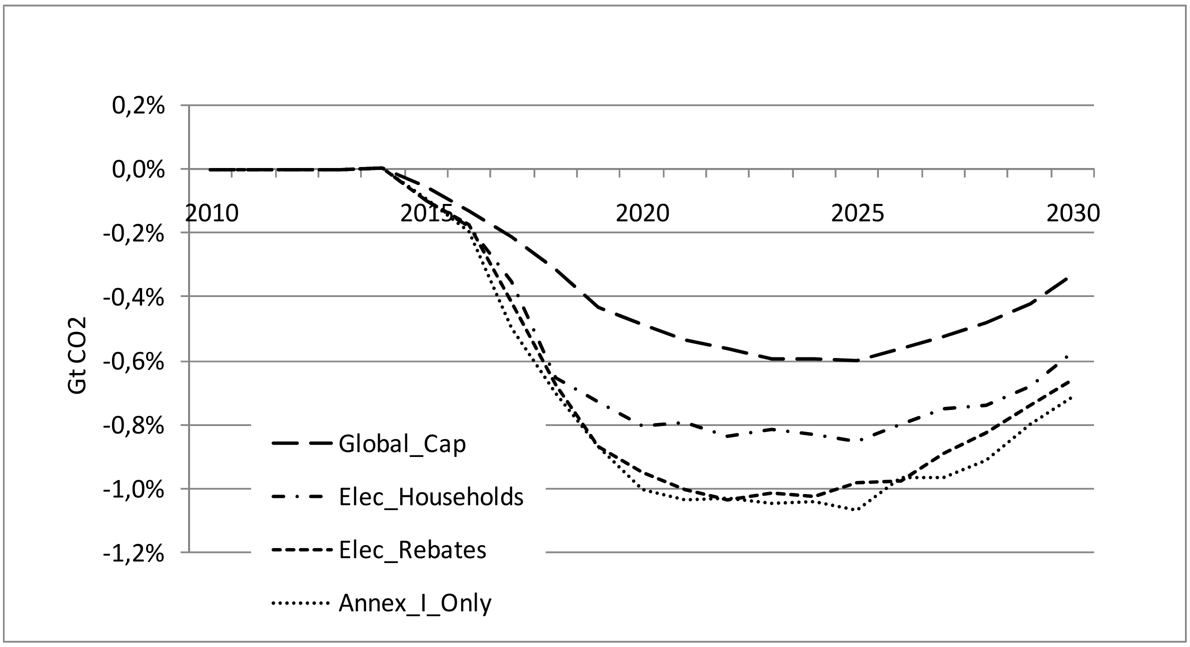


Figure 7. China GDP losses



The picture differs for Annex I countries whose GDP is always lower than in BAU (cf. Figure 8). The loss is the lowest in Global_Cap because in the other scenarios, Annex I loses market shares. Moreover, world energy prices are the lowest under Global_Cap. The highest losses occur in the Annex_I_Only and Elec_Rebates scenarios, with very close values, whereas losses are intermediate for Elec_Households. The explanation of this last result is that under that scenario, developed countries lose less market shares because developing countries producers suffer from a higher electricity price than in Annex_I_Only and Elec_Rebates.

Figure 8. GDP losses in Annex I countries



3.3. Impacts on electricity markets are much milder with rebates

As shown in Figure 9, under Global_Cap and Elec_Households, electricity price[5] almost doubles in China both compared to BAU and to the historical level. The main reason for this increase is that electricity producers pass the cost of allowances on to consumers, and a less important factor is that more expensive production technologies partly replace the relatively cheap fossil fuel technologies.

In Elec_Rebates, the electricity price increases much less: the price increase due to the CO_2 allowances is partially offset by the subsidy. More surprising is the fact that electricity price actually drops below the BAU level after 2020. There are two explanations. First, some learning-by-doing occurs in low carbon technologies, which are more used in the scenarios with climate policies. Second, in Imaclim-R, electricity producers set their price according to the complete cost of electricity generation over the life time of their power plants, using the current fossil fuel prices as the expectation of the future prices. However, in the BAU scenario we simulate, gas and oil prices do increase (cf. Figure 11 and 12 in Appendix 2), thus the electricity generation mix in BAU is too carbon-intensive compared to the ex post private optimum. A CO_2 price helps to correct this myopia by pushing producers to reduce the share of fossil fuel in their generation mix.

Electricity production (Figure 10) mirrors electricity price. In Global_Cap and Elec_Households, electricity generation is roughly stabilised in China, whereas its growth follows the BAU level in the Annex_I_Only and Elec_Rebates scenarios.

The same trends occur in other regions except Brazil, which benefits from a large share of hydropower.

[5] The electricity price shown here is the production price, i.e., including production taxes and subsidies (if any), averaged over time slices. It is not the final consumption price which differs across sectors and includes consumption taxes and subsidies.

Figure 9. Electricity prices in China

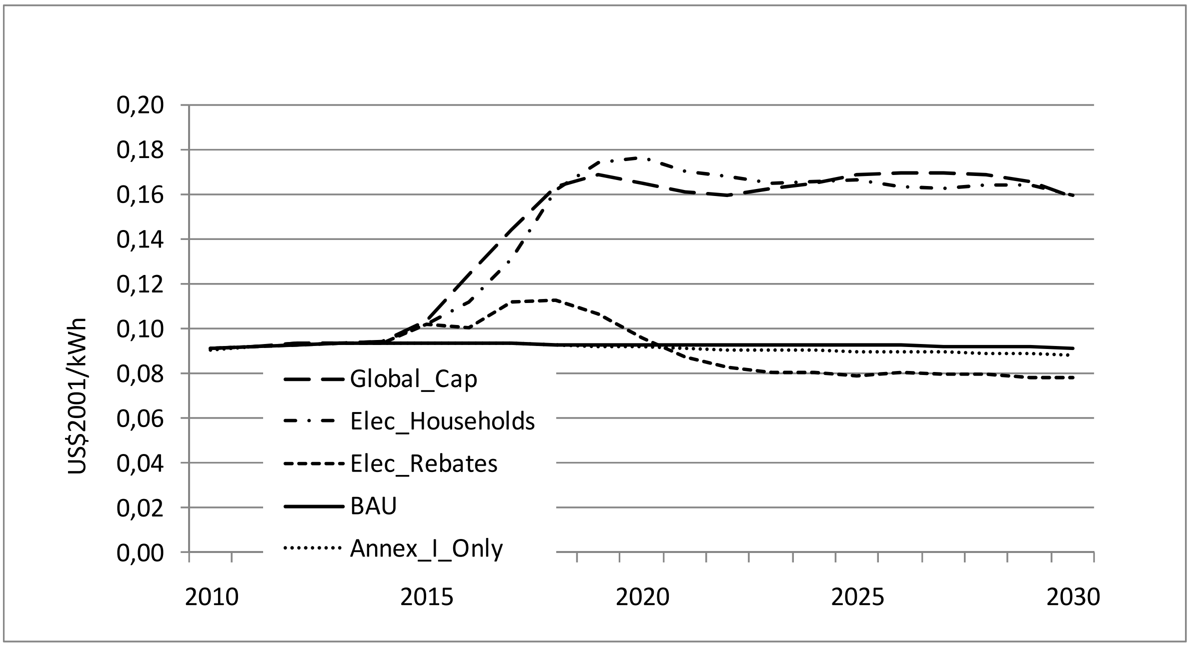
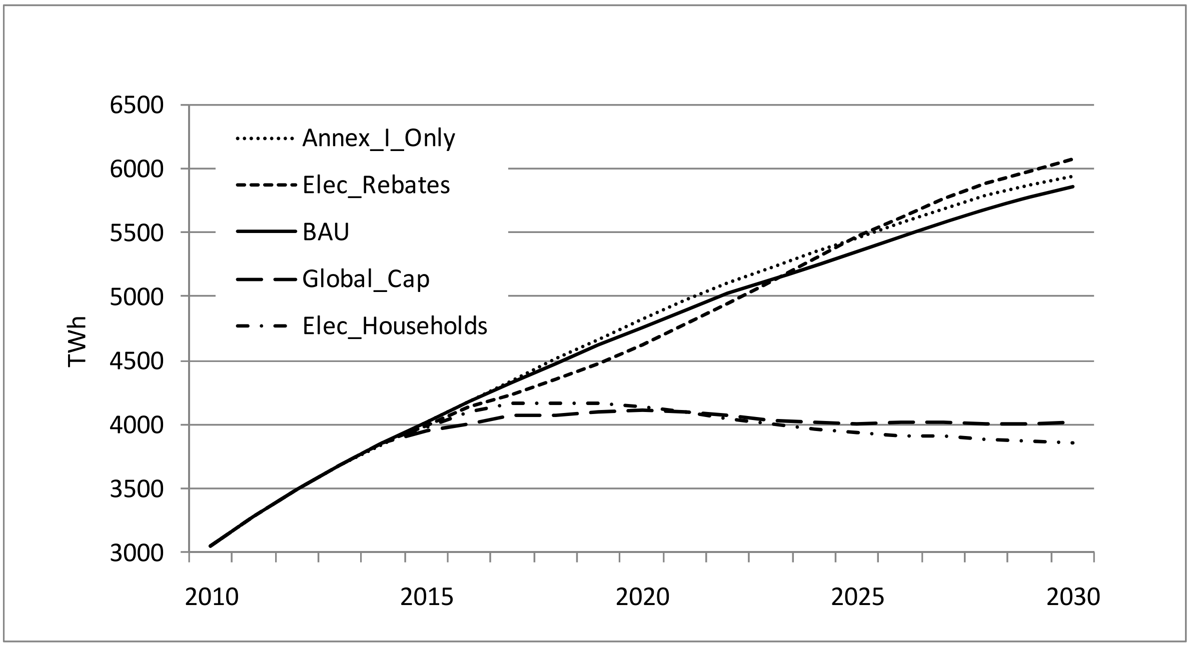


Figure 10. Electricity production in China



Conclusion

Many scholars and stakeholders have proposed sectoral targets for developing countries. We provide an economic assessment of such proposals using Imaclim-R, a global multi-region, multi-sector general equilibrium model designed to assess CO_2 emissions scenarios and policies. More precisely, we assess scenarios in which developed countries apply Kyoto-type targets whereas in developing countries, emissions in electricity generation are subject to the same CO_2 price as emissions in developed countries.

The results indicate that a sectoral target for developing countries limited to the electricity sector is able to provide around 80% of the global emission reductions of a global cap-and-trade system, for a given Annex I abatement. Moreover, if this sectoral target is implemented as an emission trading system or as an emissions tax with receipts distributed to electricity generation firms as a decrease in pre-existing production taxes or as a production subsidy, the economic impact in developing countries is milder than that of a global cap-and-trade system: GDP losses are much lower and so is the impact on the electricity price.

The scenarios assessed here are intentionally very stylized. In the real world, if a sectoral approach is applied, it will certainly feature a higher level of differentiation across regions, including *inter alia* a staged implementation with entry dates depending on development levels, price differentiation and international transfers.

In the longer term, the share of emissions from other sectors, especially transportation, will grow in developing countries as they did in developed countries. Moreover, with economic growth, the high emitters in the developing world will have a higher ability to join a global cap-and-trade system. Consequently, the sectoral approach we presented here should be seen as a transitory device rather than as an alternative to a more global approach.

Appendix 1. The Imaclim-R model

Imaclim-R is a hybrid recursive general equilibrium model of the world economy, divided into 12 regions and 12 sectors (Table 1) and solved in a yearly time step (Sassi et al. 2009). The base year of the model (2001) is built on the GTAP-6 database, which provides a balanced Social Accounting Matrix (SAM) of the world economy. The original GTAP-6 dataset has been modified to (i) aggregate regions and sectors according to the Imaclim-R mapping, and (ii) accommodate the 2001 IEA energy balances, in an effort to base Imaclim-R on a set of hybrid energy-economy matrixes. Note that the emission trajectory simulated in the business-as-usual scenario from 2002 to 2007 is very close to the IEA CO_2 emissions data (IEA, 2009): according to the IEA, CO_2 world emissions from fossil fuel combustion grew from 23.7 Gt CO_2 in 2001 to 29.0 in 2007, whereas the output of the Imaclim-R model is 29.1 Gt CO_2 for 2007.

Table 1. Regional and sectoral disaggregation of the Imaclim-R model

Regions	Sectors
USA	Coal
Canada	Oil
Europe	Gas
OECD Pacific (JP, AU, NZ, KR)	Liquid Fuels
Former Soviet Union	Electricity
China	Air transport
India	Water transport
Brazil	Other transports
Middle-East Countries	Construction
Africa	Agriculture
Rest of Asia	Energy-intensive industry
Rest of Latin America	Composite (services and light industry)

As a general equilibrium model, Imaclim-R provides a consistent macroeconomic framework to assess the energy-economy relationship through the clearing of commodity markets. Specific efforts have been devoted to building a modelling architecture allowing easy incorporation of technological information coming from bottom-up models and experts' judgement within the simulated economic trajectories. The rigorous incorporation of information about how final demand and technical systems are transformed by economic incentives is allowed by the existence of physical variables that explicitly characterise equipments and technologies (e.g. the efficiency of cars, the intensity of production in transport, etc.). The economy is then described in both money-metric terms and physical quantities, the two dimensions being linked by a price vector. This dual vision of the economy is a precondition to guaranteeing that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and consistent sets of relative prices.

The full potential of this dual representation could not be exploited without abandoning the use of conventional aggregate production functions that, after Berndt and Wood (1975) and

Jorgenson (1981), were admitted to mimic the set of available techniques and thus the technical constraints impinging on an economy: it is arguably almost impossible to find mathematical functions flexible enough to cover large departures from the reference equilibrium and to encompass different scenarios of structural changes resulting from the interplay between consumption styles, technologies and localisation patterns (Hourcade 1993). In Imaclim-R the absence of formal production functions is compensated by a recursive structure that allows a systematic exchange of information between:

- An annual static equilibrium module with Leontief production functions (fixed equipment stocks and intensities of intermediary inputs, especially labour and energy; but a flexible utilisation rate). Solving this equilibrium at some year t provides a snapshot of the economy: information about relative prices, output levels, physical flows and profit rates for each sector and allocation of investments among sectors.

- Dynamic modules, including demography, capital dynamics and sector-specific reduced forms of technology-rich models, most of which assess the reactions of technical systems to the previous static equilibriums. These reactions are then sent back to the static module in the form of updated input-output coefficients to calculate year (t+1) equilibrium.

Between two equilibriums, technical choices are fully flexible for new capital only; the input-output coefficients and labour productivity are modified at the margin, because of fixed techniques embodied in existing equipment and resulting from past technical choices. This general putty-clay assumption is critical to representing the inertia in technical systems and the perverse effect of volatility in economic signals.

Imaclim-R thus generates economic trajectories by solving successive yearly static equilibriums of the economy interlinked by dynamic modules. Within the static equilibrium, in each region, the demand for each good derives from household consumption, government consumption, investment and intermediate uses from the production sectors. This demand can be provided either by domestic production or imports and all goods and services are traded on world markets. Domestic and international markets for all goods – excluding labour – are cleared by a unique set of relative prices that depend on the demand and supply behaviours of representative agents. The calculation of this equilibrium determines relative prices, wages, labour, quantities of goods and services, and value flows.

The dynamic modules shape the accumulation of capital and its technical content; they are driven by economic signals (such as prices or sectoral profitability) that emerge from former static equilibriums. They include the modelling of (i) the evolution of capital and energy equipment stock described in both vintage and physical units (such as number of cars, housing square meter, transportation infrastructure), (ii) of technological choices of economic agent described as discrete choices in explicit technology portfolios for key sectors such as electricity, transportation and alternative liquid fuels, or captured through reduced form of technology rich bottom up models, and (iii) of endogenous technical change for energy technologies (with learning curves).

In this framework, the main exogenous drivers of economic growth are population and labour productivity dynamics. However, international trade, particularly that of energy commodities, and imperfect markets for both labour (wage curve) and capital (constrained capital flows, varying utilisation rates of productive capacities), significantly impact on economic growth.

Appendix 2. Impact on world energy and CO_2 prices

The world prices of oil, natural gas and coal are endogenous and result from demand dynamic, availability of substitutes and depletion of resources (cf. Waisman et al., 2010, for a presentation of this part of the model).

As shown in Figure 11, the world energy prices are the highest in BAU and the lowest in Global_Cap. More generally, the higher the emissions, the higher the energy prices, because the implicit supply curve of fossil fuels is upward-slopping.

Figure 11. Oil world price

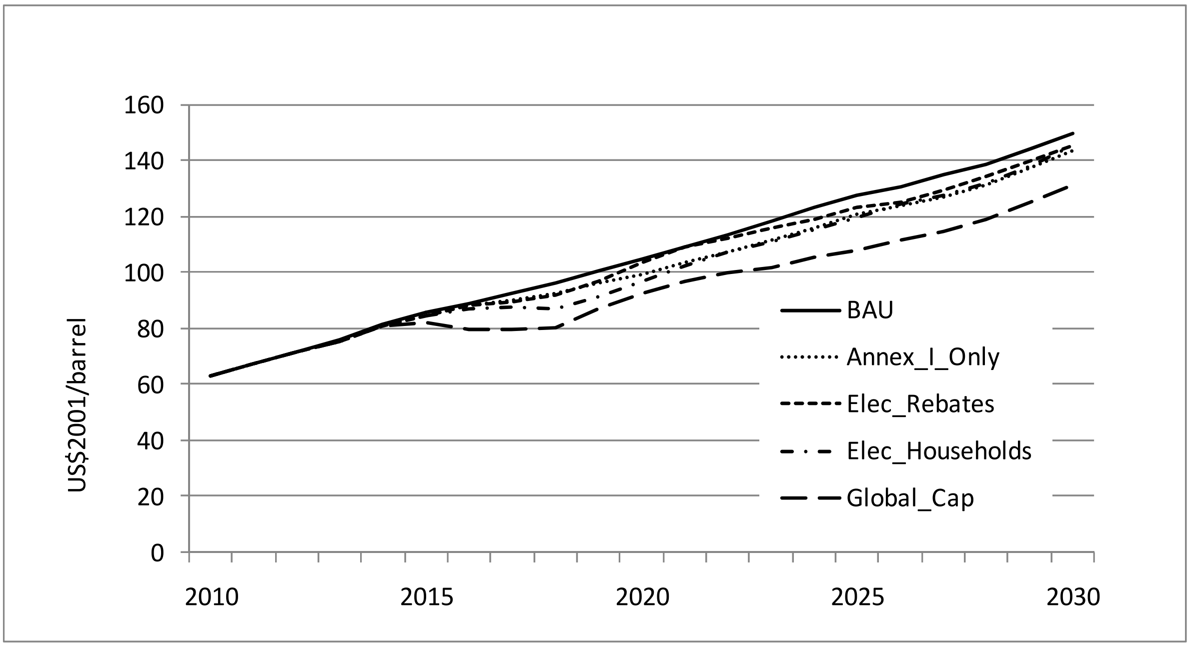


Figure 12. Gas world price

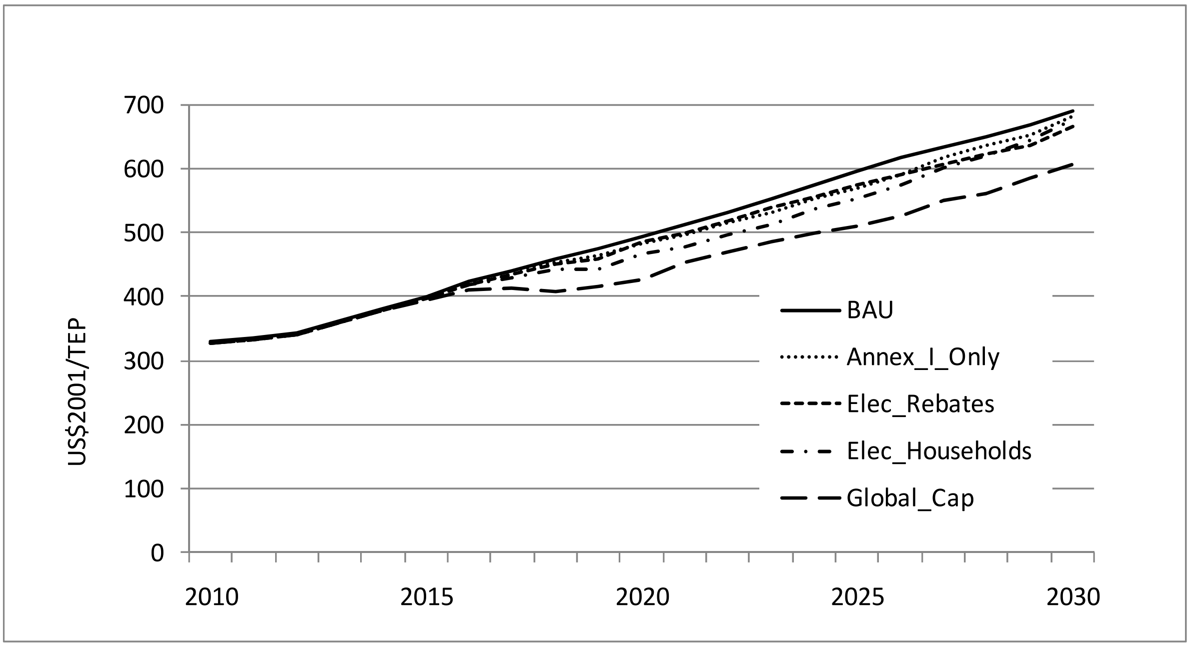
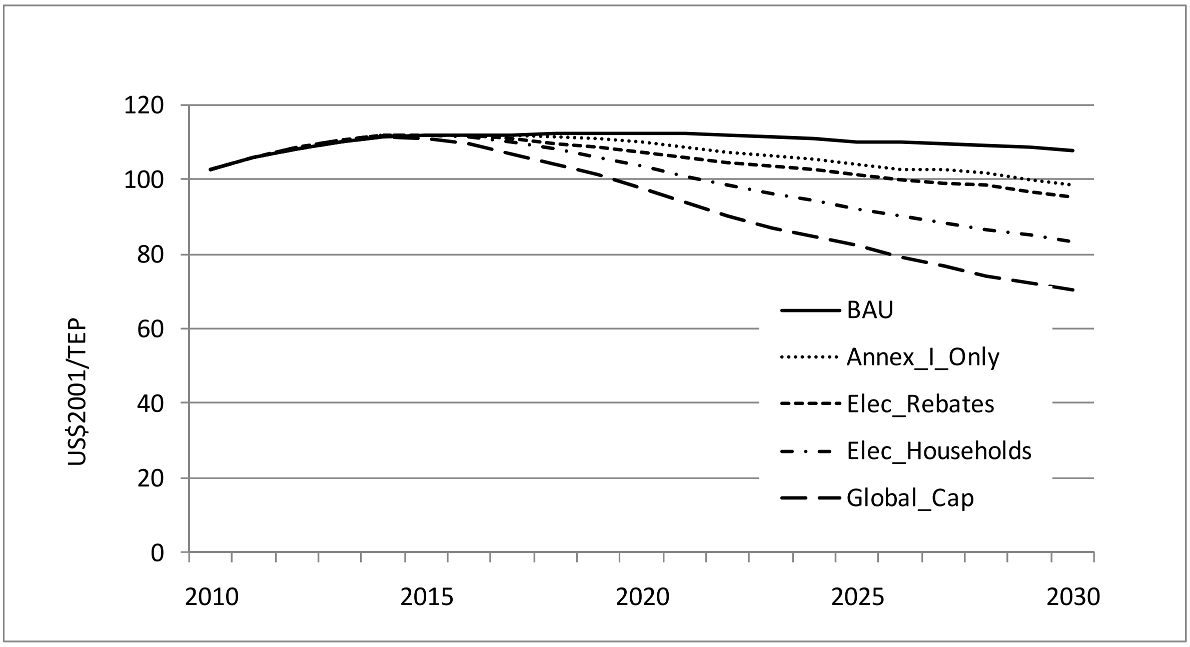
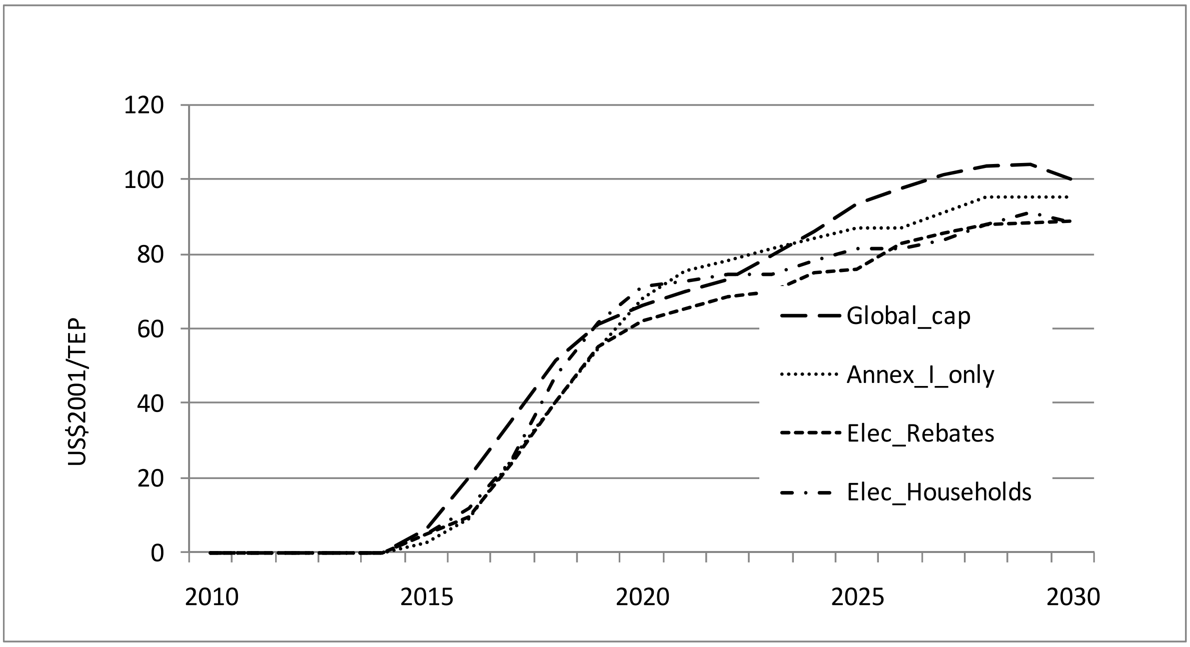


Figure 13. Coal world price



As we can see in Figure 14, the CO_2 price is almost equal across all scenarios but a little higher in Global_Cap. The explanation is that in this scenario, the fossil fuel prices are lower, so a higher CO_2 price is required to reach a given emissions level in Annex I countries.

Figure 14. CO_2 price



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