

Negative emissions and ambitious climate policies in a second best world:

A general equilibrium assessment of technology options in the electricity sector

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Abstract

This paper examines the role of electricity production from biomass with and without carbon capture and storage in sustaining low CO₂ emission pathways to 2100. It quantifies the effect of the availability of biomass resources and technologies within a general equilibrium framework. Biomass-fed integrated gasification combined cycle technology is introduced into the electricity module of IMACLIM-R, a hybrid general equilibrium model. We assess the robustness of this technology, with and without carbon capture and storage, as a way of reaching the 550 ppm stabilization target. The impact of a uniform CO₂ tax on energy prices and world GDP is examined, together with the structure of the electricity mix. The influence of additional climate mitigation policies, such as alternative recycling of tax revenues and infrastructure policies is also discussed.

Keywords: general equilibrium model; macro-economic cost; low emission objective; electricity from biomass; carbon capture and storage; negative emissions.

Outline

Abstract	1
1 Context	2
2 The challenges of energy-economy modeling	3
2.1 Modeling the electricity sector within a general equilibrium framework	3
2.2 The case for hybrid modeling: reconciling bottom-up and top-down approaches in IMACLIM-R.....	4
2.2.1 IMACLIM-R: an innovative macroeconomic framework	4
2.2.2 The electricity module.....	5
3 Results: assessing the economic impact of climate policies	6
3.1 The impact of climate policies on the electricity sector.....	7
3.1.1 The electricity mix	7
3.1.2 CO ₂ tax and energy prices	8

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3.1.3	Limitations: the wider impact of biomass production	12
3.2	The macroeconomic effect of climate policies.....	12
3.2.1	The profile of GDP losses.....	12
3.2.2	The determinants of GDP losses	13
4	Discussion: what climate policy architecture in a second-best world?	15
5	Conclusion	16
6	References.....	17

1 Context

Reaching low climate stabilization objectives may require negative net emissions towards the end of the century (Fisher et al., 2007). Negative CO₂ emissions can be achieved through direct or indirect CO₂ removal methods, for instance by enhancing land carbon sinks through land use management, natural weathering processes or the oceanic uptake of CO₂, by the direct engineered capture of CO₂ from ambient air or by using biomass for carbon sequestration (The Royal Society, 2009). CO₂ is removed from the atmosphere through photosynthesis as vegetation grows. Stored carbon eventually returns to the atmosphere when biomass decomposes, and this carbon can be sequestered in the very long term either by cutting and burying the grown biomass (Metzger and Benford, 2001) or by combining energy production from biomass and carbon capture and storage (BECCS)². BECCS has been identified as a very promising option. In fact, many modeling exercises have shown that negative emissions produced through the deployment of CCS in combination with energy production from biomass could significantly reduce the cost of climate mitigation (Azar et al., 2006), (Wise et al., 2009), (Edenhofer et al., 2010), (Luckow et al., 2010). BECCS could be applied to a wide range of biomass-related technologies (IEA, 2011), (Global CCS Institute, 2010). However, several controversies are still associated with BECCS technologies. The large-scale deployment of carbon capture and storage technologies has yet to be proved technically and economically feasible and large uncertainties remain on the size of geological storage capacity and possible leakage from those reservoirs (IPCC, 2005). Also, the use of biomass for energy production purposes raises the question of land-use competition, its effect on agriculture prices and the associated CO₂ emissions from land-use change. This study aims at exploring the impact of the availability of biomass resources and CCS technology on the macroeconomic cost of reaching ambitious climate objectives. This modeling exercise will be carried out with IMACLIM-R, a hybrid general equilibrium model which accounts for second-best economy mechanisms and which allows for testing various climate policy architectures. The study is conducted as part of the EMF24 global modeling exercise (EMF, 2011). Section 2 lists some of the issues identified in the literature and yet to be resolved in energy-economy modeling, with particular attention to the case of electricity. It describes the answer given to these challenges by the general equilibrium model IMACLIM-R. Section 3 presents the results of the modeling exercise and quantifies the economic cost of reaching ambitious climate objectives under various technology scenarios. Section 4 discusses the impact of the architecture of climate policies on the results and section 5 concludes.

²BECCS stands for Bio-Energy with Carbon Capture and Storage. This term was first introduced in (Azar et al., 2006) and (Fisher et al., 2007).

2 The challenges of energy-economy modeling

2.1 Modeling the electricity sector within a general equilibrium framework

Long-run studies of the interaction between the electricity sector, the economy and climate policies have been traditionally performed using bottom-up approaches, often in partial equilibrium, or using top-down general equilibrium energy-economy models which conventionally represent the electricity sector in an aggregate manner.

Energy-economy modeling usually relies on the use of production functions (Solow, 1956). Conventional production functions mimic the set of available techniques and the technical constraints impinging on an economy (Berndt and Wood, 1975), (Jorgenson and Fraumeni, 1981) and often use constant elasticity of substitution (CES). However, the aggregate representation of a continuous space of technologies via production functions is only theoretically justified near the equilibrium, and the use of constant elasticities of substitution may lead to incorrectly exceed feasible technical limits in the case of large departures from the reference equilibrium (McFarland et al., 2004), (Gherzi and Hourcade, 2006). The difficulty of transposing micro-economic mechanisms at the aggregate level can be overcome using bottom-up engineering information as a way to enhance the technological realism of production functions (McFarland et al., 2004). Moreover, short-term econometric analyses have shown that modeling exercises can better reproduce the observed magnitude of the economic effect of energy price variations if they include (i) mark-up pricing to capture market imperfections (Rotemberg and Woodford, 1996) ; (ii) a putty-clay description of technologies translating the inertia in the renewal of capital stock (Atkeson and Kehoe, 1999) ; (iii) the possibility for a partial rate of utilization of installed production capacities due to the limited substitution between capital and energy (Finn, 2000) ; (iv) imperfect expectations (Fisher et al., 2007), (Downing et al., 2005).

The representation of the electricity sector thus requires the explicit and detailed description of technologies (Bhattacharyya, 1996). This high level of details requires the description of load demand curves (especially peak and non-peak) and short and long term demand, using for instance short-term marginal cost pricing as well as differentiated prices for different users (Taylor 1975). Moreover, the representation of inertia in the sector is indispensable, whether it be in the end-use sectors (Silk and Joutz, 1997) or in capital stock, leading to short-run utilization rates (Taylor, 1975). The combination of inertia and imperfect foresight causes excess and shortage of supply, creating market disequilibria in the long-run (Sterman, 2000), (Rostow, 1993). This, along with the trend towards power sector liberalization, calls for abandoning perfect foresight and using adaptive simulation models, as illustrated in (Olsina et al., 2006). Market disequilibria create business cycles in the electricity sector, as modeled by (Bunn and Larsen, 1992) and (Ford, 1999) and econometrically estimated by (Arango and Larsen, 2011). Also, electricity must be considered as a “derived demand”, that is to say not providing utility in itself, but allowing for the use of other goods or services which directly provide utility (Taylor, 1975).

Finally, specific interactions between the electricity sector and the general equilibrium framework should be considered: (i) the impact of energy prices on electricity production ; (ii) the substitution between electricity and other energies in end-use sectors (households and firms) and the wider cross-sectorial effect of electricity production on fuel prices ; (iii) the very capital intensive nature of electricity production, which may lead to crowding out effects on investment, as the electricity sector takes precedence over the other productive sectors given the “essential good” nature of electricity; (iv) the dynamics of electricity demand .

The Computable General Equilibrium model IMACLIM-R bridges the gap between these branches of the literature by capturing the general equilibrium effects of short-term dynamics in second-best economies at different time horizons.

2.2 The case for hybrid modeling: reconciling bottom-up and top-down approaches in IMACLIM-R

2.2.1 IMACLIM-R: an innovative macroeconomic framework

IMACLIM-R is a recursive, dynamic, multi-region and multi-sector hybrid Computable General Equilibrium (CGE) model of the world economy (Sassi et al. 2010), (Waisman et al., 2010)³. It is calibrated for the 2001 base year by modifying the set of balanced input-output tables provided by the GTAP-6 dataset (Dimaranan, 2006) to make them fully compatible with 2001 IEA energy balances (in Mtoe) and data on passengers' mobility (in passenger-km) from (Schafer and Victor, 2000). The model was tested against historic data up to 2006 (Guivarch et al., 2009) and covers the period 2001-2100 in yearly steps through the recursive succession of static equilibria and dynamic modules. It describes growth patterns in second best worlds (market imperfections, partial uses of production factors and imperfect expectations). In particular, it reveals the economic and technical transitory adjustments induced by the interplay between choices under imperfect foresight and the inertia of technical systems.

"Hybrid matrices" (Hourcade et al., 2006) ensure a description of the economy in consistent money values and physical quantities (Sands et al., 2005). The dual description represents the material and technical content of production processes and allows for abandoning standard aggregate production functions, which have intrinsic limitations in case of large departures from the reference equilibrium (Fronzel et al., 2002). IMACLIM-R is based on the recognition that it is almost impossible to find functions with mathematical properties suited to cover large departures from a reference equilibrium over one century and flexible enough to encompass different scenarios of structural change resulting from the interplay between consumption styles, technologies and localization patterns (Hourcade, 1993). The absence of a formal production function is compensated for by a recursive structure that allows a systematic exchange of information between an annual macroeconomic equilibrium module and technology-rich dynamic modules.

The static equilibrium represents short-term macroeconomic interactions at each date t under technology and capacity constraints. It is calculated assuming Leontief production functions with fixed intermediate consumption and labor inputs, decreasing static returns caused by higher labor costs at high utilization rate of production capacities (Corrado and Matthey, 1997) and fixed mark-up in non-energy sectors. Households maximize their utility through a tradeoff between consumption goods, mobility services and residential energy uses considering fixed end-use equipment. Market clearing conditions can lead to a partial utilization of production capacities given the fixed mark-up pricing and the stickiness of labor markets. Solving this equilibrium at t provides a snapshot of the economy at this date, a set of information about relative prices, levels of output, physical flows and profitability rates for each sector and allocation of investments among sectors.

The dynamic modules, including demography, capital dynamics and sector-specific reduced forms of models take into account the economic values of the previous static equilibrium, assess the reaction of technical systems and send back this information to the static module in the form of new input-output coefficients for calculating the equilibrium at $t + 1$. Each year, technical choices are flexible but they modify only at the margin the input-output coefficients and labor productivity embodied in the existing equipment that result from past technical choices. This general putty-clay assumption is essential to represent the inertia in technical systems and the role of volatility in economic signals. Among the dynamic modules, most energy sectors are represented via stylized bottom-up models, as is the case with the power generation sector.

³ The 12 regions are USA, Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle-East, Africa, rest of Asia, Rest of Latin America. The 12 sectors are divided as follows: three primary energy sectors (Coal, Oil, Gas), two transformed energy sectors (Liquid fuels, Electricity), three transport sectors (Air, Water, Terrestrial Transport) and four productive sectors (Construction, Agriculture, Industry, Services).

In this multisectoral framework with partial use of production factors, effective growth patterns depart from the natural rate (Phelps, 1961) given by exogenous assumptions on active population (derived from UN medium scenarios) and labor productivity (satisfying a convergence hypothesis (Barro and Sala-i-Martin, 1992) informed by historic trajectories (Maddison, 1995) and ‘best guess’ assumptions (Oliveira-Martins et al., 2005)). The structure and rate of effective growth at each point in time are endogenously determined by (i) the allocation of the labor force across sectors, which is governed by the final demand addressed to these sectors (ii) the sectoral productivities which result from past investment decisions governing learning by doing processes (ii) the shortage or excess of productive capacities which result from past investment decisions under adaptive expectations. As underlined in the RECIPE study, “imperfect foresight becomes crucial when non-optimal choices cannot be corrected frictionless because of inertias on capital stocks and behavioral routines” (Waisman et al., 2010), that is why IMACLIM features imperfect foresight to answer for path-dependencies, technological lock-ins and behavioral slow-paced alterations.

2.2.2 The electricity module

Power generation planning was one of the first public energy policies. For that reason, the electricity sector was historically the focus of important modeling efforts, leading to wide developments of bottom-up models for optimal energy planning. With 40% of the global CO₂ emissions in 2002 and a forecast of roughly 5000 GW to be built in the next 30 years (IEA, 2004), the electricity sector is a main stake of mitigation policies. It is a very capital-intensive industry, which raises short-term as well as long-term macroeconomic issues, especially when ambitious climate policies could increase capital costs (e.g. uncertainties on CCS, shifts to renewables). The very nature of the electric good calls for a specific representation. Indeed, it is a non-storable good, with some characteristics of public goods. In the electricity grid, a constant balance between power available over the grid and the power demanded by the sum of final uses (the load) must be met at all times. Production must therefore adapt to major daily and seasonal fluctuations of demand. The load curve thus should be modeled, as it plays a central role in investment decision-making.

The electricity supply module in IMACLIM-R tracks electric generating capacities over time, thus incorporating the inertia and path-dependency of the system. When deciding annual investments, the modeled electricity sector forms expectations ten years forward for demand, fuel costs, and the value of the CO₂ tax. The module then deduces an optimal mix of electricity productive capacities to face future demand at the lowest possible cost, given expected future fuel prices – meaning the marginal cost pricing of electricity supply. In this process, the profitability of production technologies depends on annual operating time covering the heterogeneity of fixed and variable costs for each technology as well as on operational technical constraints. Indeed, both long term investment choices and choices concerning putting existing capacities into operation depend on the grid load curve. The minimization of the discrepancy between current capacities and the expectedly optimal mix triggers investments for the current year to reach this optimal mix under the constraint of the amount of capital allocated to the electricity sector. This process of optimal planning with imperfect foresight takes place every year and expectations are adapted to changes in prices and demand.

The optimization process chooses among 26 different power plant technologies (15 conventional including coal, gas – and oil-fired, nuclear and hydro and 11 renewables including biomass-fired thermal plants, with or without CCS) whose characteristics are calibrated on the POLES energy sectorial model. The share of each technology in the optimal mix of producing capacities results from a competition among available technologies depending on their mean production costs for a given yearly production duration. That is, competition is differentiated to account for the fact that the capacity is expected to meet peak or base load demand. In addition, taking other constraints into account (e.g. social acceptability, investment risk, size of production units, market structure) is addressed via the representation of “intangible” costs, which translate in economic terms a given constraint when making the investment decision, however not inducing any money transfer further along when producing.

Representing this sectorial technology specification contrasts with aggregated macroeconomic functions. However, the choice of power technologies cannot simply be resolved with a simple aggregated merit-order, the representation of investment choices and operational startup of existing capacities is essential.

Our study focuses in particular on the role of electricity from biomass in the electricity sector. Following the modeling specifications of IMAGE described in (Hoogwijk et al., 2009), land resources available for biomass production dedicated to power generation are restricted to abandoned agricultural land and rest land. Biomass supply curves for electricity production are also derived from (Hoogwijk et al., 2009). The most conservative assumption of the four SRES scenarios (IPCC, 2000) was retained for the maximum global biomass production in 2050 (302 EJ/year, A2 scenario). Biomass supply curves assumed for the twelve IMACLIM regions are described in Table 1.

IMACLIM region	Biomass production potential (EJ/year)			
	Below 1 USD/GJ	Below 2 USD/GJ	Below 4 USD/GJ	Below 8 USD/GJ*
USA	0	6.9	18.7	33
Canada	0	7.9	9.4	12
Europe	0	11.8	18.8	22
OECD Pacific	1.6	16.6	18.0	34
Former Soviet Union	0.8	41.9	46.6	68
China	0	0	5.8	23
India	0.6	8.2	9.8	14
Brazil	0	5.3	14.8	24
Middle-East	0	0	1.3	8
Africa	11.6	21.8	23.9	53
Rest of Asia	0	6.9	7.0	7
Rest of Latin America	0	2.0	2.9	4
World	14.6	129.3	177.0	302

Table 1: Biomass supply curves for the twelve IMACLIM regions in the A2 scenario

3 Results: assessing the economic impact of climate policies

Following the EMF24 study protocol (EMF, 2011), the trajectory of the emissions constraint of the 450ppm policy scenario strictly requires net negative emissions after 2070, as shown on Figure 1. This very low stabilization scenario thus cannot be solved without BECCS technologies in most models. The aim of our study is to reveal the impact of the availability of biomass resources and CCS on the cost of climate mitigation. As it is impossible within the framework of this study to reach the 450ppm objective without CCS technologies, it is thus impossible to assess the impact of the unavailability of CCS on the cost of mitigation. As a result, our study will focus on 550ppm climate scenarios, for which global net negative emissions are not strictly required.

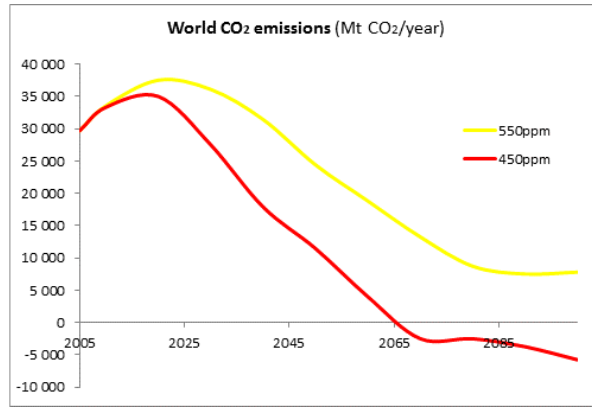


Figure 1: Emission trajectories (450 and 550ppm scenarios)

Four technology scenarios are considered, according to the availability of the CCS technology (on or off) and the availability of biomass resources (300 or 110 EJ/year). The scenarios are summarized in table 2.

CCS availability	Biomass availability	
	High (300EJ/year)	Low (110 EJ/year)
On	(1)	(2)
Off	(3)	(4)

Table 2 : Technology and resource scenarios

3.1 The impact of climate policies on the electricity sector

3.1.1 The electricity mix

Figures 2 and 3 show the electricity mix from 2010 to 2100 under a 550ppm climate constraint for the four technology and resource scenarios considered.

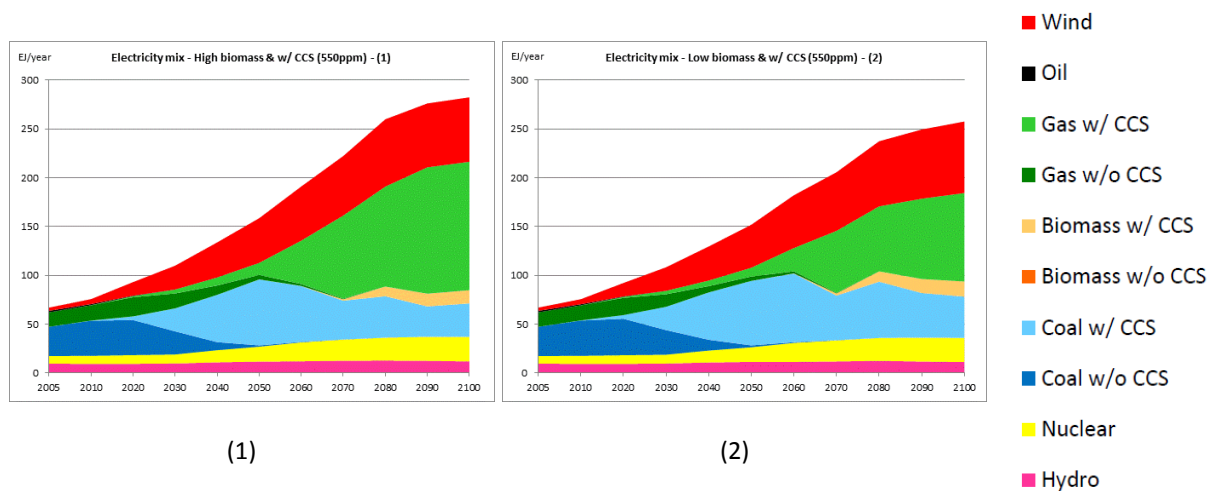


Figure 2: Global electricity mix under two biomass resource constraints (550ppm – with CCS)

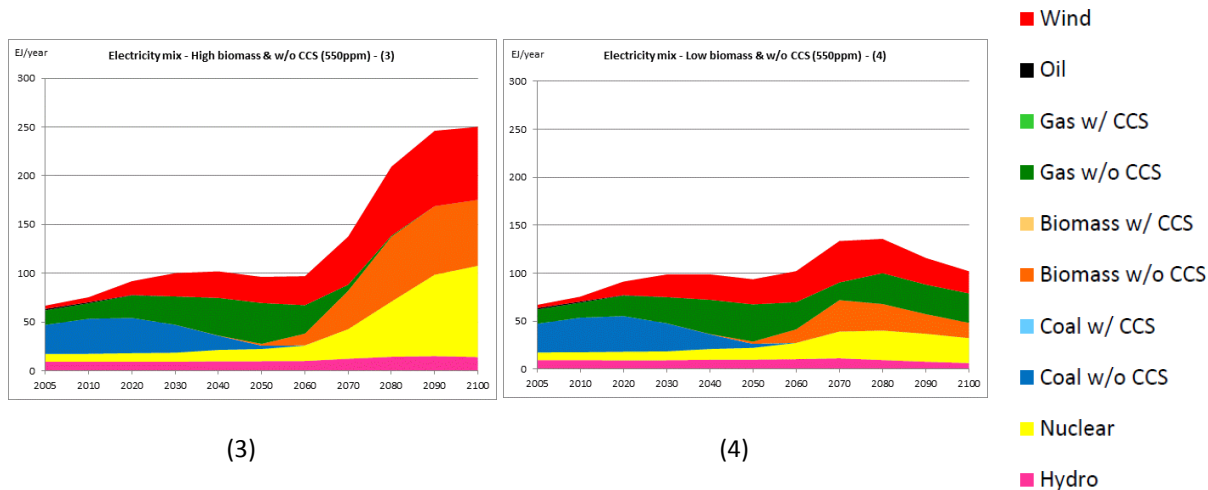


Figure 3: Global electricity mix under two biomass resource constraints (550ppm – no CCS)

When CCS is available, the size of biomass resources does not significantly alter the volume of electricity production or the nature of the mix (scenarios 1 and 2 on Figure 2). Electricity production from coal and gas without CCS is phased out by 2050 in both scenarios. The availability of biomass resources does not influence the date of entry of the BECCS technology (2050 in the case without CCS and 2070 in the case with CCS). This observation contrasts with optimization results under perfect foresight, for instance in (Magné et al., 2010), where an earlier date of entry of BECCS is required in the low resource case as a way to achieve sufficient abatement over the whole period. Our result is explained by the fact that IMACLIM is not inter-temporally optimizing, associated with the assumption of imperfect foresight.

The availability of CCS greatly influences the nature of the electricity mix, as it locks the electricity system into a path dominated by the use of fossil fuels (scenarios 1 and 2). The unavailability of CCS induces a wider deployment of renewable and nuclear energy (e.g. scenario 3 compared to scenario 1). Electricity from biomass penetrates the electricity mix earlier if CCS is unavailable (i.e. in 2050 compared to 2070 if CCS is available). This result contrasts with those of (Luckow et al., 2010) where the absence of CCS reduces the overall biomass use.

Before 2070, the electricity mix is identical in both scenarios without CCS, but one striking result is the near collapse of electricity production after that date in the constrained case (scenario 4).

3.1.2 CO₂ tax and energy prices

This collapse of electricity production in this case can be explained by looking at the evolution of electricity prices. Constraints are imposed on the deployment of electricity technologies. First, the renewal of production capacities is affected by inertia. Also, the electricity module ensures that a single technology does not dominate the supply mix. This constraint is particularly relevant in the case of nuclear power, which has raised concerns on safety issues, and in the case of some renewable energy technologies which may fail to deploy beyond a certain share of the electricity mix due to intermittency issues. The electricity price is thus driven by the availability of production technologies.

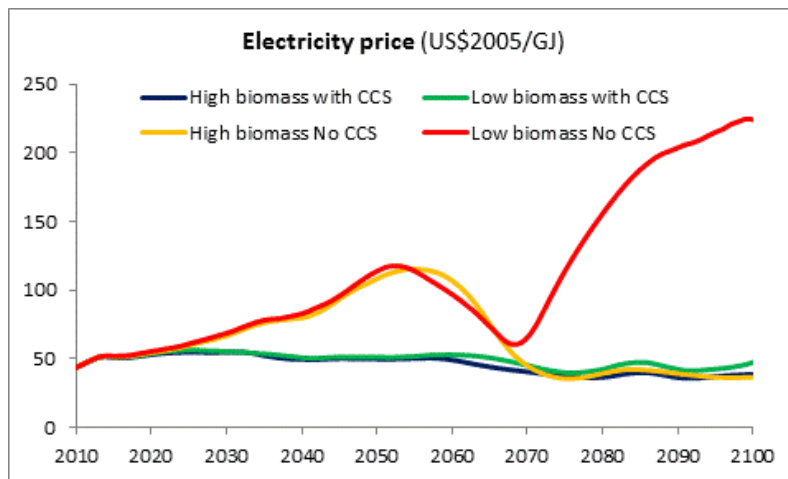


Figure 4: Average world electricity price (550ppm)

In all scenarios, the deployment of nuclear power and renewable energies is constrained to about two thirds of the electricity mix due to the reasons mentioned above. The remaining options for electricity production are biomass and fossil fuels technologies. Without the possibility of negative emissions with carbon capture and storage, the high price of biomass feedstock limits the cost-attractiveness of this technology⁴. The CO₂ tax induced by the CO₂ emissions constraint (Figure 5) affects fossil fuel prices (Figures 6, 7 and 8), which come to dominate the cost structure of electricity production from fossil fuels. For this reason, natural gas becomes the most suitable option among fossil fuels thanks to its lower emission factor. When CCS is unavailable (scenarios 3 and 4), natural gas dominates fossil fuel based electricity after 2030 (Figure 3).

In the constrained case (scenario 4), electricity prices increase very rapidly after 2070. At this date, the production of electricity from biomass becomes a crucial option to decarbonise the electricity sector in the absence of CCS. Indeed, without optimistic assumptions on the availability of biomass and CCS, very few decarbonising options remain for the electricity sector. This is illustrated by the share of electricity from natural gas. While natural gas disappears from the electricity mix to be replaced by biomass in the high biomass case, it remains a necessary option in the low biomass case. High CO₂ prices affecting fossil fuel prices are thus necessary, and the high level of the natural gas price, driven by the CO₂ tax (Figure 5), explains the steep increase in electricity prices after 2070. The impact of the technology and resource constraints can therefore be summarized as follows: while the availability of CCS creates a path dependency and conditions the evolution of the electricity mix as the system gets locked in fossil fuel use, the myopia concerning the future availability of biomass resources can result in very high unforeseen economic costs in the case of low biomass available resources.

The CO₂ tax increases the cost of energy for all productive and end-use sectors. IMACLIM endogenously determines the tax to be imposed on CO₂ emissions in order to meet the emissions constraint. The resulting tax profiles (Figure 3) reveal the very high level of the CO₂ tax in all scenarios, and more particularly in the pessimistic case where both the CCS technology and biomass resources are constrained (scenario 4).

⁴ This contrasts with the case where electricity producers benefit from a rent on negative emissions, which makes BECCS very cost-attractive provided a sufficient level of the CO₂ tax.

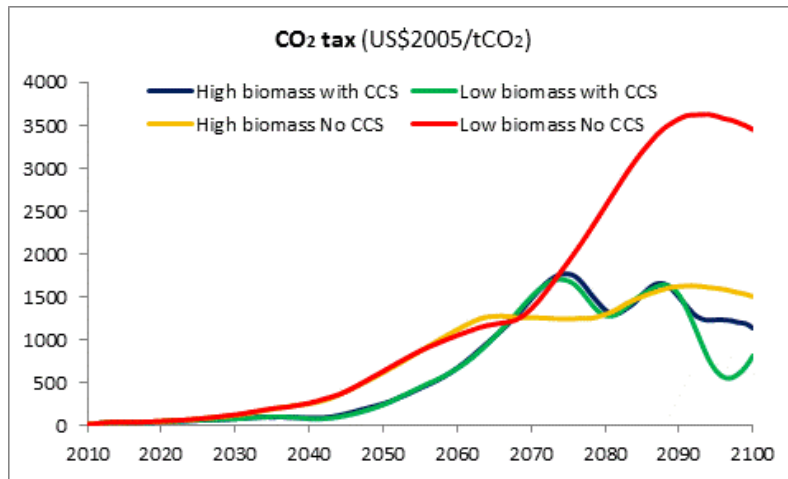


Figure 5 : World CO2 tax to reach the 550ppm target in each technology and resource scenario

The temporary switch of the tax profiles in the high and low biomass scenarios when CCS is unavailable (scenarios 3 and 4) between 2055 and 2070 can be explained by the profile of fossil fuel prices.

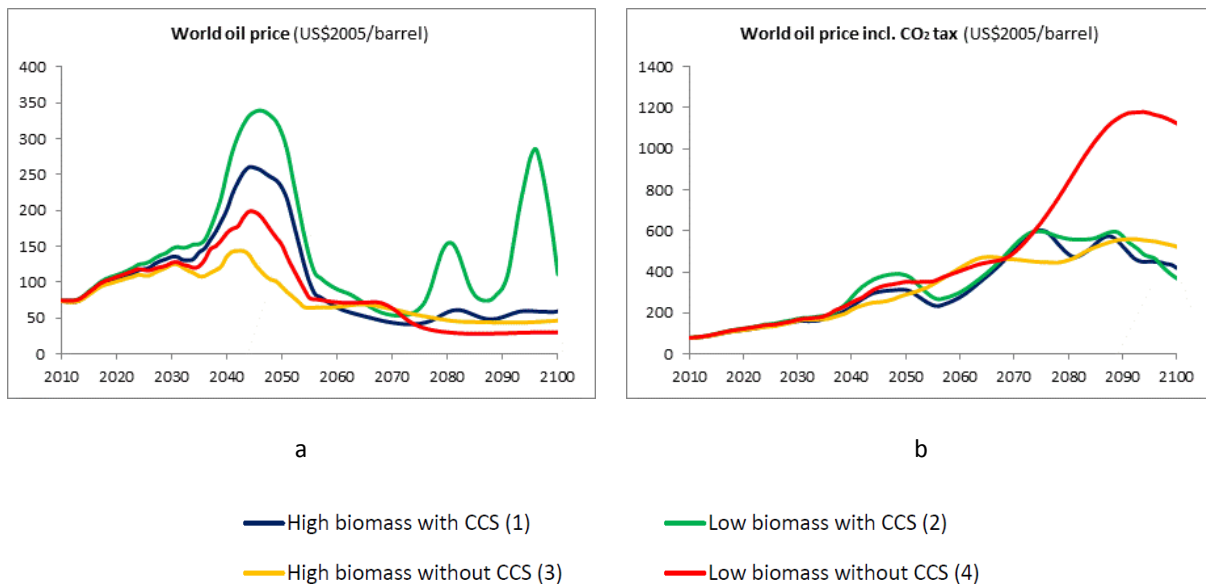


Figure 6: World oil price (550ppm)

In the case without CCS (scenarios 3 in yellow and scenario 4 in red), the oil price is higher (excl. tax, Figure 6a) in the low biomass scenario than in the high biomass scenario until 2070. After that date, the trend is reversed. This result may seem surprising at first, but in fact illustrates the role of fossil fuel prices in driving structural change. The low availability of biomass imposes a constraint on the supply of biofuel, which is a substitute to petrol. This constraint thus triggers tensions in oil markets, which are revealed by higher oil prices in scenario 4. Higher oil prices in the short and medium term (both excluding and including the CO₂ tax, cf. Figures 6a and 6b) allow the economy to decarbonize sooner. As a result, in 2060, the structure of the economy is better suited to achieve ambitious emission reductions in the low biomass case. In this case, the emissions constraint thus commands a lower CO₂ tax compared to the high biomass case (Figure 5, scenarios 3 and 4). However, the situation is reversed in 2070, when electricity from biomass becomes a crucial decarbonizing option if CCS technologies are not available. Few low-carbon options remain to fuel the expanding demand for electric transportation, and a high CO₂ tax is needed to decarbonize the transportation sector in that scenario. This shift is also visible for tax-inclusive oil prices (Figure 6b): while the CO₂ tax more than compensates the low

level of fossil fuel prices (excl. tax) over most of the period, this situation is briefly reversed in 2060 when the red and yellow curves cross.

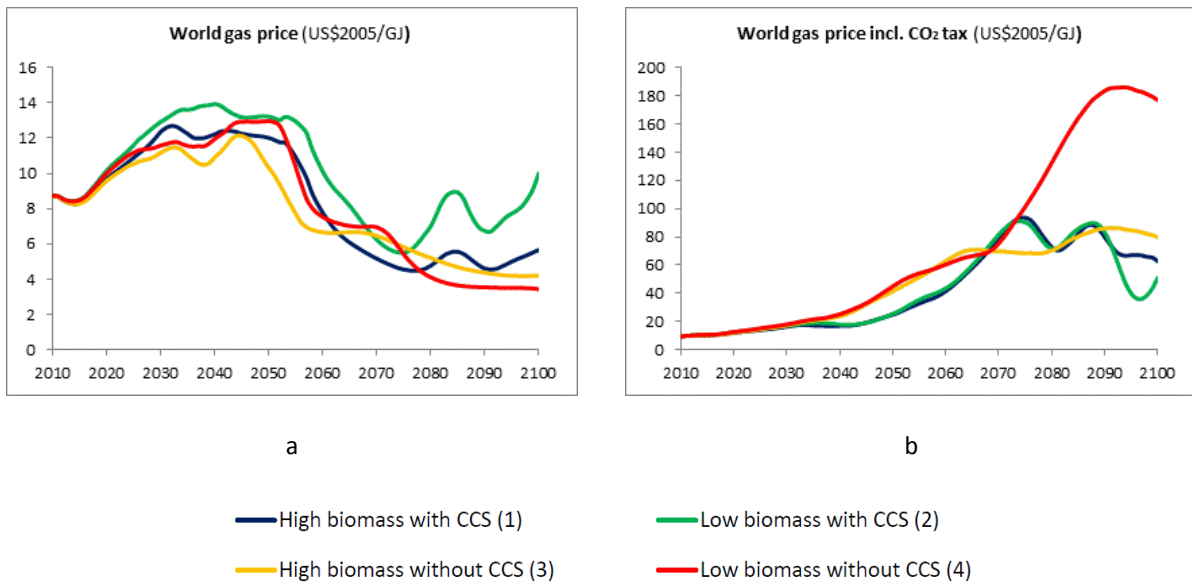
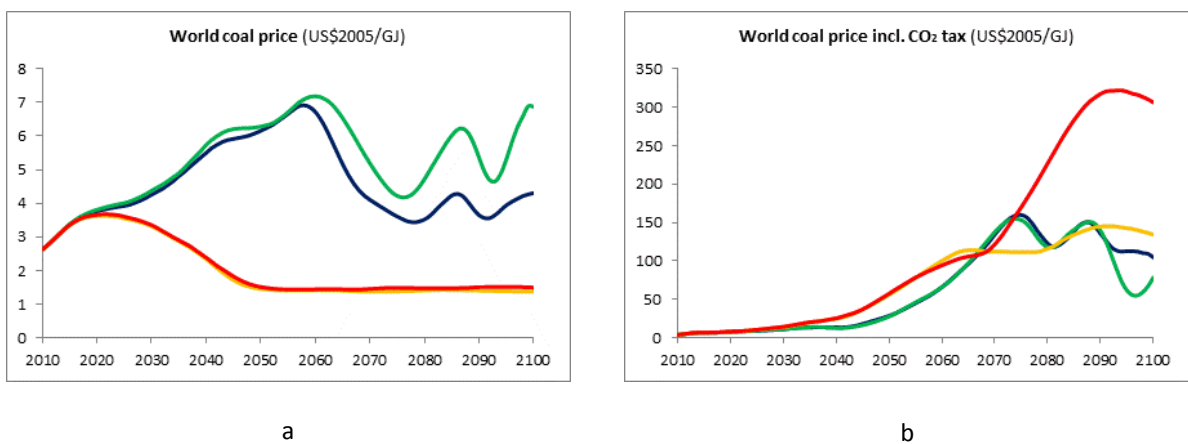


Figure 7: World gas price (550ppm)

The comparison of the CCS availability scenarios (i.e. (1) vs. (3) and (2) vs. (4)) reveals that the availability of CCS technologies increases world gas prices (excl. tax) in the short and medium term. The enforcement of strict emission constraints reduces the consumption of natural gas if CO₂ cannot be sequestered. Under climate policy, the unavailability of CCS thus constraints the deployment of electricity production technologies using natural gas in the medium and long term (cf. Figure 3). The availability of biomass affects world gas prices (excl. tax) through the level of the CO₂ tax imposed on the economy to reach the climate objective. In the pessimistic scenario, the unavailability of CCS and the low availability of biomass resources induce a very high CO₂ tax to meet the emission constraint (Figure 5), which increases world gas prices (Figure 7b), thus reducing the demand for gas, and reducing the tax exclusive price of natural gas (Figure 7a). This effect is even more striking in the case of the coal price because of its higher carbon content⁵ (Figure 8).



⁵Burning 1GJ equivalent of coal produces almost twice as much CO₂ as burning 1GJ equivalent of natural gas (0.0883 tCO₂ for coal vs. 0.0503 tCO₂ for natural gas) (MIT, 2007).



Figure 8: World coal price (550ppm)

3.1.3 Limitations: the wider impact of biomass production

Although bioenergy could play a crucial role in climate change mitigation, several issues remain. Indeed, the large scale production of biomass for energy may generate emissions from deforestation and agricultural intensification and may adversely impact food prices (Edenhofer et al., 2010).

Assuming an annual yield of 156 GJ/ha/year⁶ in 2050, the production of 300 EJ/year of biomass worldwide would require a land area of 7744 Mha, corresponding to about 15% of total land area. The influence of the increasing use of biomass energy on agricultural markets is captured through the price of the agricultural good. However, the price of land is not explicitly accounted for in the default version of the model. A land-use model (LU nexus) is coupled to IMACLIM-R in order to give an illustration of the interaction between the use of biomass energy and land prices. Preliminary results show that the price of land represents a low share of total biomass production costs compared to other productive inputs such as labor and energy. Land prices thus have a moderate effect on the supply of biomass energy. However, the explicit land-use constraint increases the macroeconomic cost of reaching the climate objective through even higher agricultural prices.

Additionally, there might be a problem of accounting and reporting for sequestered emissions. As described in (International Energy Agency 2011), the sustainability of the biomass resource needs to be assessed when reporting and accounting for emissions. As emphasized in the report, the potential pitfall that biomass used in BECCS comes from unsustainable sources in non-Annex I countries and used (and accounted for) in Annex I countries as sustainable might lead to an apparent positive outcome should be addressed. In this paper, we consider biomass grown specifically on abandoned land (i.e. not forest), which means the order of magnitude used for the resource should include no deforestation.

3.2 The macroeconomic effect of climate policies

3.2.1 The profile of GDP losses

We now examine the impact of technology and resource availability on the macroeconomic cost of reaching the 550ppm climate objective. Figure 9 shows the macroeconomic cost profile of a 550ppm climate constraint under four technology and resource scenarios. The policy instrument in place in these scenarios is a worldwide uniform CO₂ tax. The costs are shown as the difference in average GDP growth rate between the no climate policy baseline (i.e. under no climate constraint) and each of the four scenarios under climate constraint.

⁶This assumes a quadrupling of the Gross Annual Increment (GAI) proposed by Smeets et al. (2007) of 39 GJ/ha/year by 2050, which gives 156 GJ/ha/year.

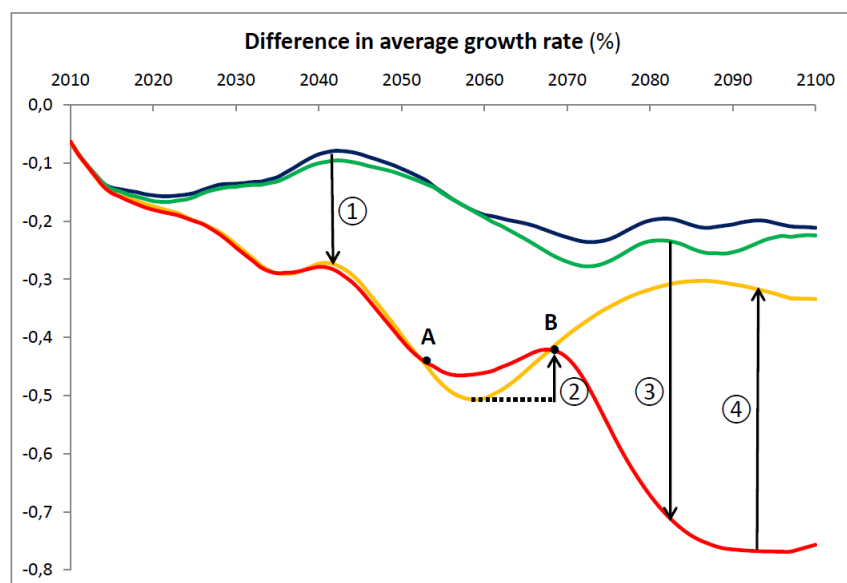


Figure 9 : Macroeconomic cost profile of 550ppm climate policy under four scenarios

The negative sign of the difference in growth rates means that the economic growth is higher in the reference scenario than in the climate policy scenarios considered. However, economic growth remains positive over the whole period, except between 2070 and 2085 in scenario 4. In the short term, the availability of the biomass resource has little influence on the results. In the longer term however, the size of biomass resources plays a crucial role when CCS is not an option. While before year 2050, the slower growth of the economy in the climate scenario is solely explained by the unavailability of the CCS technology (arrow ① on Figure 9), after 2050 the unavailability of CCS combined with the low availability of biomass resources induces extremely high costs (arrow ③). Without CCS, the larger availability of biomass greatly mitigates these costs (arrow ④): the use of biomass then becomes one of the few possible options to produce low-carbon electricity. It is interesting to note the partial economic recovery between 2060 and 2070 in the scenarios without CCS (arrow ②), due to the early transition away from fossil fuel use. While the economic recovery continues after 2070 (point B) in the high resource scenario, the low availability of biomass for electricity production greatly hampers growth after that date.

Between 2050 and 2070, the results show a faster growth in the constrained biomass case (scenario 4) compared to the high biomass case (scenario 3). This is explained by the profile of the CO₂ tax and its relation to the evolution of fossil fuel prices, as explained in section 3.1.2.

3.2.2 The determinants of GDP losses

Even in the optimistic technology scenarios, the macroeconomic cost of reaching the 550ppm climate stabilization objective is significant. The magnitude of the cost of climate policies as revealed by the modeling exercise can be explained by the interaction between the energy-economy system and the choice of policy instruments for climate mitigation within the modeling framework of IMACLIM. IMACLIM-R models a second best world with market imperfections, inertia, short-run adjustments constraints and imperfect expectations. These mechanisms inevitably induce higher cost estimates than in the case of inter-temporal optimization with perfect foresight (Fisher et al., 2007). The sole policy instrument used in the EMF24 study is a uniform CO₂ tax imposed on CO₂ emissions from fossil fuel use. A single price signal may be suited to first-best modeling frameworks; however, in the case of imperfect markets and anticipations, the absence of accompanying instruments (e.g. policies inducing a shift in investments towards public transportation infrastructure) explains the very high macroeconomic cost of climate mitigation. The effect of such policies on this cost will be examined in the discussion.

Here, we have a closer look at the influence of two major indicators of economic activity on economic growth: industrial production costs and consumer prices. The level of the CO₂ tax has a direct economic effect on all sectors. We propose here to focus on its impact on the industrial sector and on households in the optimistic technology case (scenario 1).

In the short to medium term, the share of energy in total industrial production costs is pushed up by the tax imposed on emissions from fossil fuels in the climate policy scenario. However, this trend is reversed in the very long term as low-carbon technologies take a larger share in the energy mix and become cheaper through technological learning. High carbon prices in the first half of the period have induced a structural change in industrial production towards less carbon intensive processes. The consequence of this shift is visible from 2060 with the steep decrease in the share of energy costs in overall industrial production costs. The delay in this decrease is explained by the low rate of depreciation of productive capital in the industrial sector.

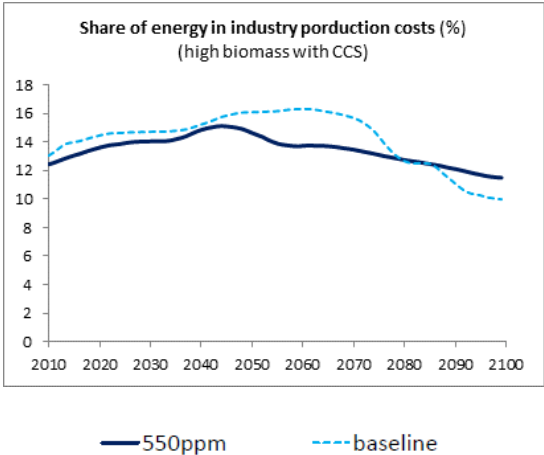


Figure 10: Energy costs as a share of total industrial production costs (%)

A second major determinant of the macroeconomic cost of climate policies is the effect of the CO₂ tax on consumer prices. This effect is revealed by the level of the consumption price index in the baseline and climate policy scenarios. The CO₂ tax unsurprisingly pushes up the consumption price index in the short term. However, early carbon pricing accelerates learning in low-carbon technologies and reduces oil demand in the short term, and thereby reduces the adverse effect of the peak oil and soaring oil prices in the medium term (Rozenberg et al., 2010), (Waisman et al., 2010).

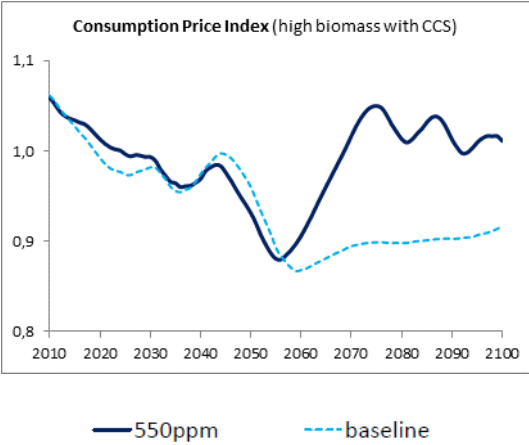


Figure 11 : Consumption Price Index

The consumption price index steeply increases after 2050. This date coincides with the deployment of electricity production from biomass. This result is partly explained by the increase in agricultural prices due to the wider use of biomass feedstock for energy production purposes. Most importantly, the consumption price index is largely driven by transportation costs after 2070. This is due to the restricted number of options available for low-carbon transport.

4 Discussion: what climate policy architecture in a second-best world?

The modeling exercise has so far assumed a uniform CO₂ tax as the sole policy instrument for climate mitigation. In fact, other policy options should be considered in order to deal with the characteristics and imperfections of 2nd best economies. Three main dimensions may reveal particularly important: the mechanism for recycling CO₂ tax revenues, the role of accompanying policies, and the timing of decarbonization for a given climate objective. The discussion will focus on the first two dimensions.

Revenues from the CO₂ tax can be recycled according to three main mechanisms: Tax revenues can be entirely redistributed to households (this is the option used in modeling exercise described above), they can be redistributed to each sector according to the paid amount (“lump-sum” principle)⁷, or they can be used to reduce labor taxes or subsidize labor costs.

Market imperfections may limit the effectiveness of a CO₂ price, in particular in the case of transportation infrastructures (Jaccard et al., 1997). Spatial planning policies can be articulated along three main axes: a shift in investments in the transportation infrastructure in favor of public modes for freight and passenger transport, the relocation of buildings to reduce passenger transport demand (e.g. in terms of commuting), and changes in industrial production to reduce freight transport needs (Waisman et al. 2010). In practice, these policies allow for a reduction of carbon-intensive mobility demand.

The rate of decarbonization in terms of absolute CO₂ emission reductions is dictated by the shape of the emissions constraint. Several emission trajectories can be derived for a given climate objective, set in terms of cumulative emissions. These trajectories are defined according to the stringency of emission reductions in the short and long term. The cost of decarbonizing the economy is influenced by the pace of technology learning of low-carbon technologies and the rate of increase in energy efficiency in all productive and end-use sectors. We examine the impact of these elements on the macroeconomic cost of climate mitigation. Figure 11 shows the impact of various policy options on the cost profile of the 550ppm mitigation scenario under optimistic technology and resource assumptions (scenario 1).

⁷ With the exception of power generation sector, for which the payoff is given to consumers.

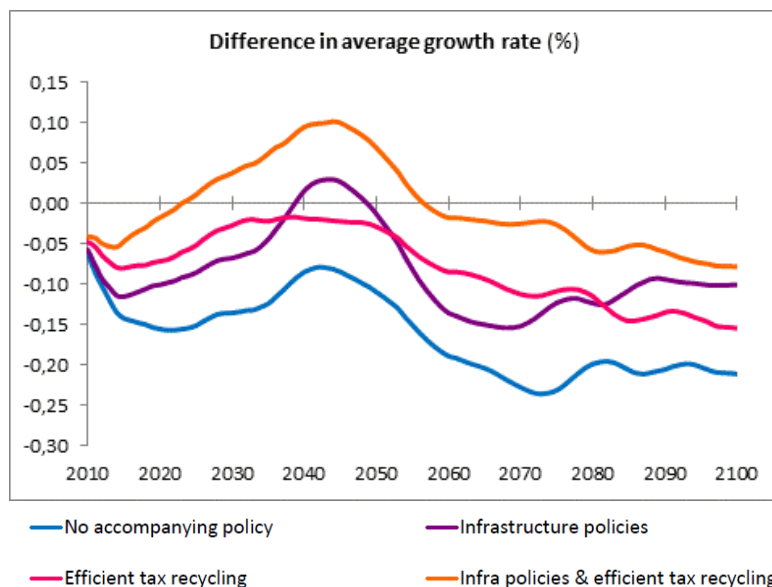


Figure 11: Cost with and without accompanying policies - (550ppm, optimistic technology case)

Carbon tax revenues are used to decrease labor taxes. This tax recycling option reduces the short and medium term costs of reaching the climate objective, as demonstrated by the comparison in Figure 11 between the “reference” climate scenario (blue) and the “efficient tax recycling” scenario (pink). As was seen earlier, short term economic losses with a single CO₂ tax are mainly explained by the increase in production costs, for instance in the industrial sector. The decrease in labor taxes reduces labor costs and overall production costs in all sectors, thus reducing economic losses compared to the reference scenario,

Accompanying infrastructure policies (labeled “Infrastructure policies” in Figure 11) aimed at reducing mobility demand significantly reduce the overall macroeconomic costs of reaching the climate objective. Their effect is particularly visible in the medium and long term. In the medium term (2030-2050), new infrastructures start reducing oil demand, thus delaying the peak oil. The associated increase in oil prices and its adverse effect on growth is partly avoided, and infrastructure policies even induce some net benefits compared to the baseline scenario without any CO₂ constraint. In the long term (after 2070), the high level of the CO₂ tax in the reference scenario follows the need to decarbonize the transportation sector. Some low carbon options are available, namely biofuels and electric vehicles, but the cost of their deployment highly depends on the pace of technical change in this sector (Waisman et al., 2010). The role of infrastructure policies in reducing mobility demand is thus crucial at that time horizon, as shown by the comparison of the trends in the difference in the average growth rate between the reference and “infrastructure policies” scenarios: infrastructure policies allow for a partial catch-up with the no constraint baseline scenario after 2070. The combination of these policies and the use of CO₂ tax revenues to reduce labor taxes allows for net economic benefits of climate policies in the medium term.

5 Conclusion

The modeling exercise has revealed the sometimes complex dynamics of the links between electricity production and prices, fossil fuel markets and demand for energy at various time horizons. The availability of carbon capture and storage creates a path dependency and conditions the evolution of the electricity mix and the low availability of biomass resources can result in very high unforeseen economic costs. CCS technologies are beneficial to the economy in the short to medium term, when fossil fuel resources remain available and relatively cheap. However, in the longer term, economies are locked in an electricity mix that is greatly

dependent on the use of fossil fuels. The unavailability of CCS combined with the low availability of biomass resources induces extremely high costs in the long term. Without CCS, the use of biomass then becomes one of the few remaining options to produce low-carbon electricity, making biomass a robust technology option.

The macroeconomic cost of climate mitigation is in part driven by the increase in production costs in all sectors and the increase in consumer prices, due to higher fossil fuel prices. The study revealed that additional policy options should be implemented to achieve ambitious climate objectives. In particular, the combination of recycling tax revenues to reduce labor taxes and the implementation of infrastructure policies may induce net economic benefits.

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