Energy Economics 34 (2012) S15–S28

Contents lists available at SciVerse ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

"Investments and public finance in a green, low carbon, economy"

Carlo Carraro [a,b,c], Alice Favero [a,b,c,d], Emanuele Massetti [b,c,d,*]

[a] University of Venice, Italy
[b] Fondazione Eni Enrico Mattei, Italy
[c] Euro-Mediterranean Center for Climate Change, Italy
[d] Yale University, United States

ARTICLE INFO

Article history:
Received 7 January 2012
Received in revised form 13 August 2012
Accepted 30 August 2012
Available online 7 September 2012

JEL classification:
O32
Q43
Q50
Q54
Q54
Q58

Keywords:
Climate change mitigation
Carbon tax
Negative emissions

ABSTRACT

The paper evaluates the impacts on investments and public finance of a transition to a green, low carbon, economy induced by carbon taxation. Four global tax scenarios are examined using the integrated assessment model WITCH. Taxes are levied on all greenhouse gases (GHGs) and lead to global GHG concentrations equal to 680, 560, 500 and 460 ppm CO_2-eq in 2100. Investments in the power sector increase with respect to the Reference scenario only with the two highest taxes. Investments in energy-related R&D increase in all tax scenarios, but they are a small fraction of GDP. Investments in oil upstream decline in all scenarios. As a result, total investments decline with respect to the Reference scenario. Carbon tax revenues are high in absolute terms and as share of GDP. With high carbon taxes, tax revenues follow a "carbon Laffer" curve. The model assumes that tax revenues are flawlessly recycled lump-sum into the economy. In all scenarios, the power sector becomes a net recipient of subsidies to support the absorption of GHGs. In some regions, with high carbon taxes, subsidies to GHG removal are higher than tax revenues at the end of the century.

1. Introduction

A large literature has assessed the macroeconomic cost of stabilising Greenhouse Gas (GHG) concentrations, with various assumptions on the environmental stringency of the adopted policy tool, on the technologies available, on the cost of those technologies, on the timing and on the degree of international cooperation (Cf. Barker et al., 2007; Clarke et al., 2009; Edenhofer et al., 2009; Edenhofer et al., 2010 for some overviews). The macroeconomic cost of a climate policy – e.g. the discounted loss of Gross Domestic Product (GDP) – is an important indicator and it certainly deserves an important place in both the academic and the policy debate on climate change mitigation. However, this is not the only piece of information on the economic implications of climate policy that policy makers and the business community would need to better plan future investments and policy decisions. For example, there is a large and growing demand for estimates of investments, particularly in the power sector, needed to cut GHG emissions and for estimates of the financial implications of climate policy, both at the national and international levels.[1] Policy makers and the business community are indeed interested in knowing when and where investments should flow and how large they should be. A transition to a green economy may indeed require excessive financial resources and crowd out productive investments.

It is important to stress that estimates of macroeconomic costs and investment needs inform on two very different aspects of climate policy and should not be confused. Investments are expenditures that increase productive capital. They imply a financial transfer from one agent to another, from one sector of the economy to another sector, or from one generation to the next. If investments are re-distributed among capital assets that have the same productivity (i.e. that yield the same output per unit of investment) the level of macroeconomic

* Corresponding author at: Yale School of Forestry and Environmental Studies, 195 Prospect St, New Haven, CT 06511, United States.
E-mail address: emanuele.massetti@yale.edu (E. Massetti).

[1] As a response of this growing interest on climate finance, the International Panel on Climate Change (IPCC) has introduced a Chapter on "Cross-cutting Investment and Finance Issues" in the forthcoming Fifth Assessment Report.

0140-9883/$ – see front matter
http://dx.doi.org/10.1016/j.eneco.2012.08.036

activity is not affected. Macroeconomic costs arise when investments are redistributed from more productive uses to less productive uses. This loss of productivity generates a lower level of output, which is the true net cost of climate policy for the economy as a whole.

The Integrated Assessment Modeling community has been prolific in providing estimates of the macroeconomic costs of climate policy but has virtually neglected investment needs. For example, among the large set of papers collected in two recent Special Issues published by Energy Economics – one on the Energy Modeling Forum (Clarke et al., 2009) and the other on the Asia Modeling Exercise (Calvin et al., forthcoming) – none presents estimates of investment needs.

There is only a handful of studies that estimate investments flows and their distribution and financial implications using large-scale, sophisticated, energy-economy models (Edenhofer et al., 2009; IEA, 2010; IEA, 2011; Riahi et al., 2012). Among those, only Riahi et al. (2012) use the full potential of an Integrated Assessment Model (MESSAGE) to provide information on investment needs with a high technological detail under a mix of climate and energy policies which are consistent with a 2 °C above pre-industrial level in 2100. Edenhofer et al. (2009) provide little information on aggregate investments in the power sector. IEA (2010) and IEA (2011) provide estimates with high technological detail but the analysis is limited to 2030.[2]

This paper contributes to this embryonic literature by providing a detailed assessment of investment needs and public finance in four representative green economy scenarios generated using the Integrated Assessment Model WITCH (Bosetti et al., 2006; Bosetti et al., 2007; Bosetti et al., 2009a).[3] The transition to a green, low carbon, economy is induced by four tax scenarios stabilising GHG concentrations in the atmosphere to 680, 560, 500 and 460 ppm CO_2-equivalent (ppm CO_2-eq) by the end of the century. As a consequence, global mean temperature increases in 2100 between 3.2 °C and 2 °C above pre-industrial levels. We examine the impact of climate policy on investments and current expenditures in the power sector, on investments in Research and Development (R&D) in the energy sector, on investments in the oil sector and on other aggregate non-energy investments. Investments in the power and in the oil sectors are endogenous in the model, as are energy demand and fuel prices. R&D investments are also endogenous. We complete our assessment of climate finance by providing estimates of carbon tax revenues and their implications on public finance.

With respect to Riahi et al. (2012), this paper analyses four climate policy targets instead of one. By focusing on climate policy alone instead than on a mix of climate and energy policies, we can establish a relationship between the stringency of the tax (the long-term concentration target) and investment needs. We also provide estimates of R&D investments in the energy sector and an assessment of carbon tax revenues, which are not part of the analysis of Riahi et al. (2012). Finally, we present separate results for OECD and non-OECD countries. Unfortunately, we cannot provide estimates of investments in demand side energy efficiency and in power transmission and distribution as in Riahi et al. (2012), because they are not modelled in WITCH.

The rest of the paper is organised as follows. Section 2 presents an overview of the WITCH model. Section 3 introduces the scenario design and presents basic facts of the Reference scenario and of the policy scenarios. Section 4 discusses the relationship between macroeconomic costs, investments and carbon tax revenues in a green, low carbon, economy. Section 5 illustrates changes in the optimal mix of investments and current expenditures in the power sector, investments in the oil upstream sector and in other sectors of the economy. Section 6 deals with investments in innovation. Section 7 examines revenues from carbon taxes. The final section provides a brief summary of our findings.

[2] Other studies have presented estimates of investment needs without using full-fledged economic models (UNFCCC 2007; McKinsey 2009; Bredenkamp and Pattillo 2010; United Nations 2010). For a survey of this literature see Haites (2011).

[3] More precisely, we consider taxes on all GHG emissions but we use the expression "carbon tax" for simplicity.

2. An overview of the WITCH model

WITCH – "World Induced Technical Change Hybrid" – is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate damages (cost–benefit analysis) or on the optimal responses to climate mitigation policies (cost-effectiveness analysis) (Bosetti et al., 2006, 2007, 2009a).

WITCH has a peculiar game-theoretic structure that allows modelling both cooperative and non-cooperative interactions among countries. As in RICE (Nordhaus and Yang, 1996), the non-cooperative solution is the outcome of an open-loop Nash game: thirteen world regions interact non-cooperatively on the environment (GHG emissions), fossil fuels, energy R&D, and on learning-by-doing in renewables. Investment decisions in one region affect investment decisions in all other regions, at any point in time. In this paper the non-cooperative solution is used to build both the Reference and the policy scenarios. Since we focus on a cost-effectiveness framework, we do not include the feedback of climate change on the economy which is instead present when the model is used for cost–benefit analysis.[4]

Each region's social planner maximizes the present value of discounted log-utility of per capita consumption. WITCH's top–down framework guarantees an efficient, fully intertemporal allocation of investments, including those in the energy sector, without ad-hoc assumptions as in simulation models. WITCH is a truly dynamic model in which investment decisions are taken with perfect foresight. This means, for example, that carbon prices expected in the future affect present investment decisions. There is no uncertainty and it is possible to perfectly foresee the environment – in terms of economic growth, population, price of inputs – in which investments decisions will be taken.

WITCH is a hybrid model because it combines features of both top–down and bottom–up modelling: the top–down component consists of an intertemporal Ramsey–Cass–Koopmans optimal growth model in which the economy of each region is divided in two large sectors that are perfect substitutes. On the one side we have the oil extraction sector and on the other side the rest of the economy. The energy input of the aggregate 'non-oil' production function has been expanded by means of nested Constant Elasticity of Substitution (CES) functions to provide a rich description of energy supply.

The 'non-oil' CES production function combines a Cobb–Douglas aggregate of capital–labour and energy services with an elasticity of substitution equal to 0.5; energy services are produced combining the energy input and knowledge capital in a CES nest with elasticity of substitution equal to 1.7. The energy input is a CES combination of electric and non-electric energies. Further detail is provided in Bosetti et al. (2006, 2007, 2009a).

Energy sector dynamics is fully endogenous. Energy services demand depends on the (endogenous) relative prices of capital, labour and energy inputs. Each region's social planner determines the optimal level of electricity generation and the optimal technology mix by investing in nine different power generation capacity stocks, one for each technology.[5] Therefore investments in the power sector are an output of the model. WITCH does not use exogenous levelized

[4] The lack of a climate feedback into the economy might lead to biased estimates of future investment patterns. We might overestimate investments in the Reference scenario and underestimate investments in the carbon tax scenarios. However, the bias would likely affect years at the end of the century (mitigation measures have significant impacts on average temperature beyond 2070) while we focus most of the analysis on the first half of the century.

[5] Range of investment costs in power generation technologies across the thirteen world regions in base year (2005): wind (1467 US$/kW), nuclear (1590–2587 US$/kW), hydro-power (1777 US$/kW), pulverized coal (966–2072 US$/kW), oil (819–1365 US$/kW), natural gas (629–1050 US$/kW), integrated gasification combined cycle (IGCC) coal with carbon capture and storage (3173 US$/kW), natural gas with carbon capture and storage (2538 US$/kW). IGCC power plants with CCS can also be used with a mix of coal and biomass. There is a backstop power generation technology which becomes competitive only after investing in a dedicated knowledge stock. The backstop substitutes nuclear linearly.

cost of electricity. The cost of electricity is determined endogenously and implicitly as the shadow value of the resources employed in power generation, coherently with a Ramsey-type optimal growth setup. Therefore, the cost of electricity generation closely follows the pattern of the endogenous interest rate and of fuel prices. As the economy grows, the interest rate declines and so does the opportunity cost of capital. At the same time, fuels become more costly. Therefore, capital intensive technologies (e.g. wind and nuclear) become more and more attractive with respect to fuel intensive technologies (e.g. natural gas) even without a penalty on emissions.

In this paper we use a recent version of the model in which biomass can be used together with coal in Integrated Gasification Combined Cycle (IGCC) power plants with carbon capture and storage (CCS) technologies. The cost of the biomass feedstock is determined on the basis of regional supply cost curves obtained by the land use model GLOBIOM (Havlík et al., 2011). GLOBIOM accounts for residual emissions associated with the full life cycle of growing, harvesting and transporting the biomass. The WITCH and GLOBIOM models are not fully integrated, which might cause inconsistencies due to potential feedback effects of climate policy on optimal land use. However, conservative assumptions on biomass supply expansion in GLOBIOM limit this problem.

Output in the oil sector is produced by means of eight different capital goods that represent installed capacity for oil extraction in eight different oil categories, from conventional light crude to extra heavy tar sands, with specific extraction costs and emission coefficients. Each region has a fixed endowment of oil resources for each category and can freely invest to increase extraction capacity in any category. Each capital good in the oil sector produces oil as output and the output is aggregated linearly across all categories. Investments are subtracted from the budget constraint of the economy. Regions can either consume oil production or sell it abroad. When oil is consumed domestically it represents a net cost for the 'non-oil' sector. When it is sold abroad oil become a source of foreign revenues. All oil production is valued using the international market clearing price. The model is calibrated to reproduce the share of 'oil' and 'non-oil' GDP in the base year. The relative size of the two sectors in the following years is determined endogenously (see Massetti and Sferra, 2010 for a description of the oil sector).

The international price of gas is indexed to the price of oil. This is certainly an area that deserves further research because a global market for natural gas is quickly emerging as a response to a large, geographically fragmented, expansion of production, particularly in the USA. The price of coal increases with world cumulative consumption.

In WITCH, emissions arise from fossil fuels used in the energy sector and from land use changes and forestry that release carbon sequestered in biomasses and soils (LULUCF). Emissions of CH_4, N_2O, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) and SO_2 aerosols, which have a cooling effect on temperature, are also identified. Emissions from LULUCF and non-CO_2 gases are exogenous in the Reference scenario. Abatement cost curves for non-CO_2 gases and for LULUCF emissions are also exogenous (see Bosetti et al., 2009a). A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHG concentrations. An exogenous path of aerosols affects radiative forcing.

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

The major pitfall of WITCH is the low detail in non-electric energy technologies. In particular, WITCH lacks a detailed set of end-use energy technologies and does not distinguishes between transport and residential energy uses. Accordingly, investment dynamics in the non-electric sector is not analysed in this paper.[6]

A final word of caution is necessary to interpret our findings. WITCH – as all other integrated assessment models – is designed to produce scenarios and not forecasts. Investments scenarios are certainly accurate and the model is sufficiently well calibrated to produce a realistic picture of the energy sector. However, the aim of the model is to show the major forces at play and how investments and tax revenues change when a climate policy is introduced in an optimisation setting. Therefore, the model does not deliver forecasts about the future but a series of optimisation scenarios to identify the main consequences of climate policy.

The base year is 2005 for calibration, all monetary values are in constant 2005 USD, market exchange rates are used to convert national currencies.

3. Scenarios

The international community has taken a precautionary stance by formally introducing the objective to keep global mean temperature increase below 2 °C in 2100 in the Cancun Agreements signed at the 16th UNFCCC Conference of Parties in 2010. However, this ambitious target has not been followed by either binding or informal adequate commitments to reduce GHG emissions. This leaves wide uncertainty on future mitigation efforts and consequent GHG concentrations by the end of the century. Hence, in this paper four long-term policies that constrain GHG concentrations below 680, 560, 500 and 460 ppm CO_2-eq in 2100 are considered in order to capture various possible outcomes of future global climate policy.

The assumed policy tool is a global tax on all GHG emissions from 2015. Each carbon tax scenarios is named after the long-term concentration target. The tax trajectories are determined by solving the model using a cap-and-trade policy tool with borrowing and banking for the 460 ppm CO_2-eq target. With both "when" and "where" flexibilities, we find the optimal level and growth rate of the carbon price.[7] We then use the carbon price in the tax scenario, in order to avoid unnecessary assumptions on the distribution of emission allowances and thus separating efficiency from equity considerations. The same growth rate of the 460 carbon tax is then used to determine the other tax trajectories. Tax revenues are recycled lump-sum in the economy. Fig. 1 illustrates how the taxes evolve until 2100, with a focus on 2015–2050.

Our analysis of the costs and investment needs of a green, low carbon, economy assumes an ideal policy framework with full immediate co-operation among all countries. Each country introduces the same tax on all GHG emissions. Despite offering an optimistic view of future international climate policy, with these assumptions we avoid overly complex scenarios and we are able to present a benchmark case against which more realistic policy and market settings can be assessed.[8]

[6] The model was recently expanded to include a transport sector representing the use and profile of light domestic vehicles (LDVs) but this latest version was not used in this study (see Bosetti and Longden, 2012).

[7] We cannot apply a simple Hotelling rule because the interest rate in WITCH is endogenous and different across regions and diminishes over time as the marginal productivity of capital increases. OECD regions start with interest rates at about 5% and non-OECD regions with interest rates around 7–10%. The tax grows at about 10% in 2015 and at about 2% at the end of the century. For a wider discussion of the carbon market with banking and borrowing in WITCH see Bosetti et al. (2009b).

[8] It must be noted, however, that climate architectures which contemplate delayed actions or limits to key low-carbon technologies are likely to jeopardize the achievement of the 450 ppm $CO_{2\text{-eq}}$ target (Clarke et al., 2009).

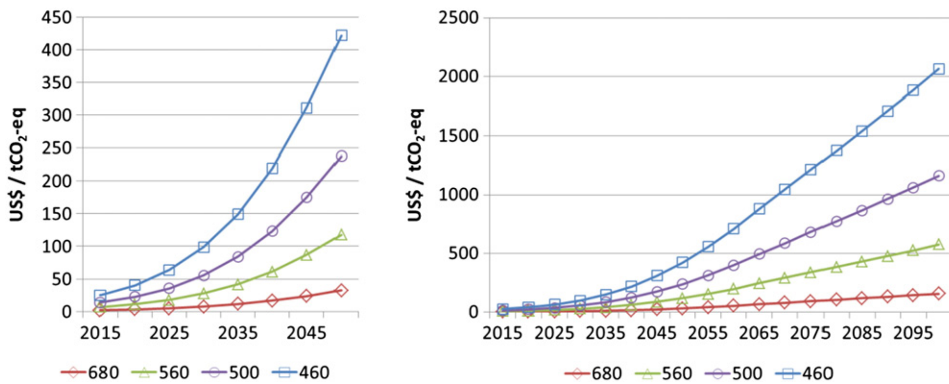

Fig. 1. Carbon tax scenarios 2015–2050 (left panel) and 2015–2100 (right panel). Notes: Global taxes on all GHG emissions. Each carbon tax scenario is named after the long-term concentration target.

Table 1
Socio-economic and energy use indicators.

Scenario	Year	Population (billions)			Gross World Product (trillions)			Total primary energy supply (EJ)			Electricity demand ('000 TWH)			Energy intensity of output (index, 2010 = 1)			Carbon intensity of energy (index, 2010 = 1)		
		OECD	Non OECD	World	OECD	Non OECD	World	OECD	Non OECD	World	OECD	Non OECD	World	OECD	Non OECD	World	OECD	Non OECD	World
Reference	2010	1.11	5.80	6.90	40	13	53	210	236	445	10.9	8.8	19.7	1.00	1.00	1.00	1.00	1.00	1.00
	2030	1.17	7.15	8.31	59	43	102	233	397	629	13.9	20.2	34.1	0.75	0.52	0.73	1.00	1.06	1.04
	2050	1.17	8.01	9.19	79	95	173	253	566	819	17.0	35.0	52.0	0.61	0.34	0.56	1.07	1.11	1.11
680	2010	1.11	5.80	6.90	40	13	53	210	236	445	10.9	8.8	19.7	1.00	1.00	1.00	1.00	1.00	1.00
	2030	1.17	7.15	8.31	59	43	102	226	379	604	13.5	18.8	32.3	0.73	0.50	0.71	0.97	1.04	1.02
	2050	1.17	8.01	9.19	79	94	172	229	484	712	15.6	27.5	43.1	0.55	0.29	0.49	0.97	1.04	1.03
560	2010	1.11	5.80	6.90	40	13	53	209	235	444	10.9	8.8	19.7	1.00	1.00	1.00	1.00	1.00	1.00
	2030	1.17	7.15	8.31	59	43	102	207	342	550	12.7	16.2	28.9	0.67	0.45	0.65	0.88	1.00	0.96
	2050	1.17	8.01	9.19	78	92	170	204	402	606	14.9	22.2	37.2	0.50	0.25	0.43	0.70	0.80	0.78
500	2010	1.11	5.80	6.90	40	13	53	208	237	444	10.7	8.8	19.5	1.00	1.00	1.00	1.00	1.00	1.00
	2030	1.17	7.15	8.31	59	43	101	201	316	518	12.6	14.3	26.9	0.66	0.42	0.61	0.84	0.93	0.90
	2050	1.17	8.01	9.19	77	91	168	219	400	619	15.4	22.3	37.7	0.54	0.25	0.44	0.54	0.64	0.61
460	2010	1.11	5.80	6.90	40	13	53	207	237	444	10.6	8.8	19.4	1.00	1.00	1.00	1.00	1.00	1.00
	2030	1.17	7.15	8.31	59	42	101	202	297	499	12.5	13.5	26.0	0.66	0.40	0.59	0.78	0.82	0.81
	2050	1.17	8.01	9.19	77	90	167	213	383	595	15.6	22.7	38.3	0.53	0.24	0.43	0.40	0.51	0.48

3.1. The Reference scenario

In the Reference scenario, no policy to stabilise GHG concentrations is introduced. Countries behave non-cooperatively on the global commons. Table 1 and Table 2 report major economic, energy and climate variables in the Reference and in the carbon tax scenarios. The scenarios cover the whole century, but we restrict most of our analysis to 2050.[9]

In the Reference scenario, total primary energy demand grows over the whole first half of the century, fuelled by population, economic growth and by abundant, relatively inexpensive, fossil fuels. Most of the increment of energy demand is expected to come from non-OECD countries, in particular from fast-growing Asian economies.[10] Electricity demand grows at a faster pace than total primary energy supply, revealing a long-term increment of both the absolute and relative weight of the power sector in satisfying energy needs.

Although total energy demand is increasing, all economies become more energy efficient. In particular, the contraction of output energy intensity is stronger in non-OECD countries, because they start from relatively higher inefficiencies. Carbon intensity of energy is increasing in both OECD and non-OECD countries, due to a growing use of coal for power generation. Coal remains the cheapest option to fuel power plants for the whole century in our Reference scenario and the gap with the other fossil fuels increases as time goes by (see Table 2). Accordingly, the share of coal over total fossil fuel demand increases from 32% in 2010 to 39% in 2050.

The large expansion of total primary energy supply and the relatively faster expansion of coal – the fuel with the highest content of carbon per unit of energy – explain the continued growth of CO_2 emissions from fossil fuels. CO_2 emissions from other sectors and emissions of other GHG grow exogenously (see Table 2 for data until 2050 and Fig. A1 in Appendix A for data until 2100). CO_2 concentrations grow from 391 ppm in 2010 to 503 ppm in 2050, up to 714 ppm in 2100: an average increment of 2.8 ppm/year between 2010 and 2050 (3.6 ppm/year between 2010 and 2100), substantially higher than the average 2.0 ppm increase per year from 1995 to 2005 (see Forster et al., 2007). Concentrations of all GHG achieve 604 ppm CO_2-eq in 2050 and 942 ppm CO_2-eq in 2100 (see Table 2 and Fig. A1 in Appendix A). The global mean temperature increases by 4 °C above pre-industrial levels in 2100.

3.2. The carbon tax scenarios

Global emissions of all GHGs are equal to 43.6 Gt CO_2-eq in 2010. What is their expected dynamics on our four scenarios? In the 460 and 500 tax scenarios, GHG emissions decline from 2015. In 2050

[9] The full set of results for each scenario is available upon request.

[10] Regional disaggregation: USA, WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Australia, South Africa and South Korea), CAJAZ (Canada, Japan and New Zealand), TE (Transition Economies), MENA (Middle East and Northern Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), EASIA (East Asia), China, LACA (Latin America and the Caribbean), and India. The OECD group consists of: USA, WEURO, EEURO, KOSAU, and CAJAZ. Mexico is part of the OECD but in the model it is included in the LACA region.

Table 2
Fossil fuels consumption and price, emissions and climate data.

Scenario	Year	Coal consumption (EJ)			Oil consumption (EJ)			Natural gas consumption (EJ)			Price of fossil fuels			CO_2 emissions from fossil fuels (Gton CO_2)			GHG emissions (Gton CO_2-eq)			Concentrations of CO_2 (ppm)	Concentrations of GHG (ppm CO_2-eq)	Temperature (°C above pre-industrial level)
		OECD	Non OECD	World	OECD	Non OECD	World	OECD	Non OECD	World	Coal ($/short ton)	Oil ($/barrel)	Natural gas ($/cubic feet)	OECD	Non OECD	World	OECD	Non OECD	World			
Reference	2010	51	72	123	92	76	169	46	46	92	55	66	0.008	13.1	15.8	29.0	16.1	28.6	44.7	391	443	0.85
	2030	55	139	193	100	138	238	49	68	117	59	96	0.012	14.5	28.1	42.7	17.6	42.1	59.8	438	519	1.39
	2050	63	215	278	105	197	302	49	91	140	67	127	0.016	17.0	42.2	59.2	19.9	59.3	79.2	503	630	2.11
680	2010	51	72	123	92	76	169	46	46	92	55	66	0.008	13.1	15.8	29.0	16.1	28.6	44.7	391	443	0.85
	2030	49	123	172	99	136	235	48	67	115	59	95	0.012	13.8	26.5	40.3	16.3	38.5	54.8	436	513	1.38
	2050	42	142	184	99	187	286	47	88	134	65	126	0.016	13.9	33.7	47.6	16.0	47.5	63.5	489	599	2.03
560	2010	51	72	122	92	76	168	46	46	92	55	66	0.008	13.1	15.8	28.9	16.0	28.6	44.6	391	443	0.85
	2030	33	94	127	95	130	224	46	64	110	58	94	0.012	11.4	22.9	34.3	13.7	33.2	46.9	430	501	1.35
	2050	30	83	113	85	161	246	38	72	110	62	129	0.016	9.0	21.6	30.6	10.2	30.6	40.8	461	550	1.91
500	2010	47	71	118	93	77	170	47	47	94	55	65	0.008	12.9	15.9	28.8	15.8	28.7	44.5	391	443	0.85
	2030	29	71	100	92	127	219	44	62	106	58	87	0.011	10.5	19.7	30.2	12.7	29.1	41.8	425	494	1.34
	2050	28	78	106	74	142	216	44	73	117	60	107	0.013	7.4	17.1	24.5	8.6	25.9	34.5	445	526	1.81
460	2010	45	69	114	94	78	172	48	48	96	55	64	0.008	12.8	15.8	28.6	15.7	28.6	44.3	391	443	0.85
	2030	29	61	89	87	118	206	43	55	97	57	81	0.010	9.8	16.2	26.0	11.5	24.0	35.5	420	486	1.33
	2050	30	73	104	54	106	161	40	72	112	60	93	0.012	5.3	13.1	18.4	6.5	21.9	28.4	432	510	1.74

they drop to 28.4 (−56% wrt Reference and −22% wrt 2010) and 34.5 Gt CO_2-eq (−64% wrt Reference and −36% wrt 2010), respectively. In the 560 and 680 tax scenarios, GHG emissions peak in 2040 and in 2050, at 47.8 and 63.5 Gt CO_2-eq, respectively. In 2050, emissions are equal to 40.8 Gt CO_2-eq in the 560 tax scenario (−48% wrt Reference, −9% wrt 2010); in the 680 tax scenario, emissions in 2050 are equal to 63.5 Gt CO_2-eq (−20% wrt Reference, +42% wrt 2010). In 2100, global GHG emissions are equal to 7.8 (460 scenario), 12.1 (500 scenario), 26 (560 scenario) and 43.6 (680 scenario) Gt CO_2-eq. Radiative forcing is equal to 2.8 (460 scenario), 3.2 (500 scenario), 3.8 (560 scenario) and 4.8 (680 scenario) W/m^2. The four scenarios lead to a temperature increase of 2.0, 2.2, 2.5 and 3.2 °C in 2100 with respect to pre-industrial levels (see Table 2 until 2050 and Fig. A1 in Appendix A until 2100).

Table 1 shows that the four policy scenarios induce further efficiency improvements wrt the Reference scenario and also invert the trend of carbon intensity of energy. Energy efficiency plays the most important role when taxes are low: for the 680 and 560 scenarios and until 2030 for the 500 and 460 scenarios. With high taxes it becomes optimal to reduce the carbon intensity of energy by increasing the share of zero – or low-emission – power generation technologies. Non-OECD countries are faster than OECD countries in reducing the energy intensity of output but slower in reducing the carbon intensity of energy. Despite the large energy efficiency gains which lead to a large drop of energy demand with respect to the Reference scenario, non-OECD countries have a growing demand of energy in all tax scenarios due to high population and economic growth. Oil consumption and natural gas consumption decline over time, both in OECD and non-OECD regions, with respect to the Reference scenario and with respect to 2010. The use of coal declines in the first decade and then it increases due to the expansion of ICCG coal power plants with CCS.

4. Macroeconomic costs, investments and tax revenues

Climate policy is costly in all four scenarios (Fig. 2). Carbon taxes direct investments towards more expensive technologies and push energy efficiency beyond the optimal level found in the Reference scenario. This drives the economy away from the most productive allocation of resources and reduces GDP (without accounting for the environmental benefit). Costs – measured as the difference between the discounted sum of Gross World Product (GWP) in the tax scenarios and the Reference scenario over the whole century – are highly non-linear in mitigation effort: reducing the increase of temperature by 0.8 °C (from 4.0 °C to 3.2 °C above the pre-industrial level) costs 0.4% of GWP, an additional contraction of 0.6 °C (from 3.2 °C to 2.6 °C) costs about 1% of GWP, a further reduction of 0.4 °C (from 2.6 °C to 2.2 °C) costs about 0.4% of GWP and the final reduction of 0.2 °C to reach the 2 °C target costs about 0.8% of GWP (discounting

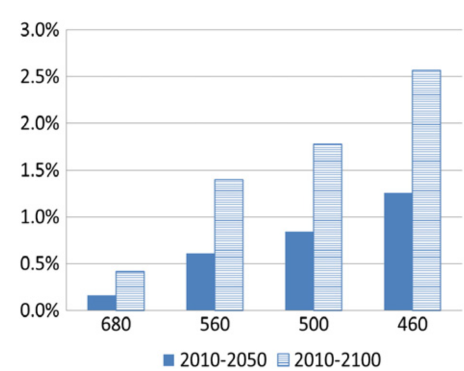

Fig. 2. Cost of the carbon tax policy. Notes: Climate policy costs measured as the difference between the discounted sum of Gross World Product (GWP) in the tax scenarios and discounted GWP in the Reference scenario, divided by discounted GWP in the Reference scenario, over 2010–2050 and 2010–2100. A uniform 5% interest rate is used for discounting.

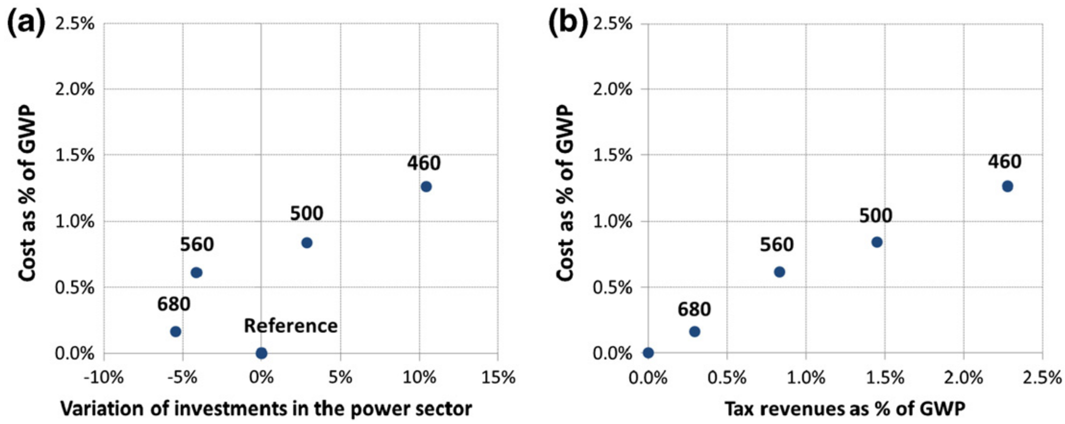

Fig. 3. Relationship between investments in the power sector and policy cost (a) and between tax revenues and policy cost (b). Notes: Each data point in Panel a illustrates the relationship between the percentage change of discounted global investments in the power sector and policy costs from 2010 to 2050, in the Reference and in the carbon tax scenarios. Panel b illustrates the relationship between costs and tax revenues, both discounted and aggregated over 2010–2050.

using a constant 5% interest rate). In absolute terms, the 560 tax scenario costs US$ 32 trillion and the 460 tax scenario costs US$ 46 trillion. The cost range for two similar long-term concentration targets found in the Energy Modeling Forum 22 is US$ 5.1–44.3 trillion (550 ppm CO_2-eq) and US$ 12–123 trillion (450 ppm CO_2-eq) (Clarke et al., 2009).

As argued in the Introduction section, macroeconomic costs, investment expenditures and taxation costs (tax revenues) should not be confused. Panel a of Fig. 3 illustrates the relationship between the percentage change of discounted global investments in the power sector from 2010 to 2050 induced by the tax scenarios and the discounted GWP losses from 2010 to 2050. The figure does not establish causality but more modestly portrays observed optimal combinations of investment variations and output losses. Fig. 3 shows that investments are more elastic to carbon pricing than aggregate output. In the highest tax scenario investments increase by 10% while costs are approximately equal to 1.3%. Most interestingly, a contraction of investments in the power sector is consistent with positive macroeconomic costs. Fig. 3 also shows that it is possible to conceive a case in which aggregate investments in the power sector do not change but the policy is costly from a macroeconomic point of view. Using incremental investments in the power sector as a measure of the costs of climate policy and vice versa is therefore unambiguously wrong. An exclusive focus on the macroeconomy hides important sectoral effects, difficulties and bottlenecks due to a potential large redistribution of investments. An exclusive focus on sectoral effects might exaggerate the overall welfare impact of climate policy.

Panel b of Fig. 3 illustrates the relationship between costs and tax revenues, both discounted and aggregated over 2010–2050. It shows an almost linear relationship between tax revenues and macroeconomic costs at global level. The correlation between taxes and costs is clearly positive but quite flat. Again, tax revenues should not be used to assess the cost of climate policy and vice versa. An exclusive focus on tax revenues might exaggerate the cost of the policy because it neglects the possibility of redistributing taxes to producers and consumers. An exclusive focus on macroeconomic costs may hide problems in managing large fiscal revenues in a sustainable and efficient way, as noted with greater detail in Section 7 below.

Panel b of Fig. 3 hides large regional differences. Fig. 4 expands Panel b of Fig. 3 at regional level for all the tax scenarios under examination. At regional level, the relationship between carbon tax revenues and policy costs is not as straightforward as at global level: it is positive but loose. It is indeed possible that two countries with the same carbon tax revenue might have very different costs, and vice versa, for two main reasons. First, with a carbon tax countries abate emissions up to the point at which the marginal cost is equal to the marginal benefit. The cost of abatement is given by the area underlying the marginal abatement cost curve. The tax revenue is obtained by multiplying residual emissions by the carbon tax. Therefore, the relationship between costs and tax revenues depends on the shape of the marginal abatement cost curve. There exist cases in which abatement is very low, and thus costs are low (relative to GDP), while carbon tax revenues are high and vice versa. Second, countries that export oil suffer net losses from a contraction of the demand and price of oil. Those countries experience high indirect policy costs. The relationship between carbon tax revenues and policy costs is thus influenced by factors that go beyond the shape of the marginal abatement cost curves.

In the 460 panel of Fig. 4, two regions with very high carbon tax revenues have low macroeconomic costs (South Asia and Sub-Saharan Africa). The regions with the highest GDP loss have high, but not the highest tax revenues because they suffer from the contraction of the oil market (Middle East and North Africa and Transition Economies). Western Europe and the USA have almost identical tax revenues but the USA has costs twice as big as Western Europe. In general, the group of non-OECD economies has higher tax revenues as share of GDP than the group of OECD economies. This raises some concerns that are discussed in Section 7.

5. Investments in a low-carbon economy

In Section 3.2 we briefly mentioned that climate policy first induces energy savings and then a decarbonization of energy supply. Unfortunately, investments in end-use technologies cannot be assessed because the model does not have such level of detail. We can instead provide a close-up on the power sector, oil upstream investments and overall macroeconomic investments.

Zero – or low-carbon – generation technologies have investment costs per unit of installed capacity higher than the traditional coal or gas fired power plants that they are meant to replace.[11] Renewables have also lower hours of operation than traditional fossil fuels technologies. Therefore, installed capacity needs to rise to meet the same demand for electricity. Had the electricity demand of the Reference scenario to be supplied by low-carbon technologies, the total amount of investments in the power sector would certainly increase. However, one of the cheapest ways to reduce carbon emissions is to increase energy efficiency (Table 1). There are thus two forces at play: more technologically advanced power plants will increase investment costs per unit of installed capacity, but at the same time installed capacity will decline as electricity demand declines (with respect to the Reference scenario). The optimal balance

[11] See Edenhofer et al. (2011) for an overview of costs of renewable electricity generation.

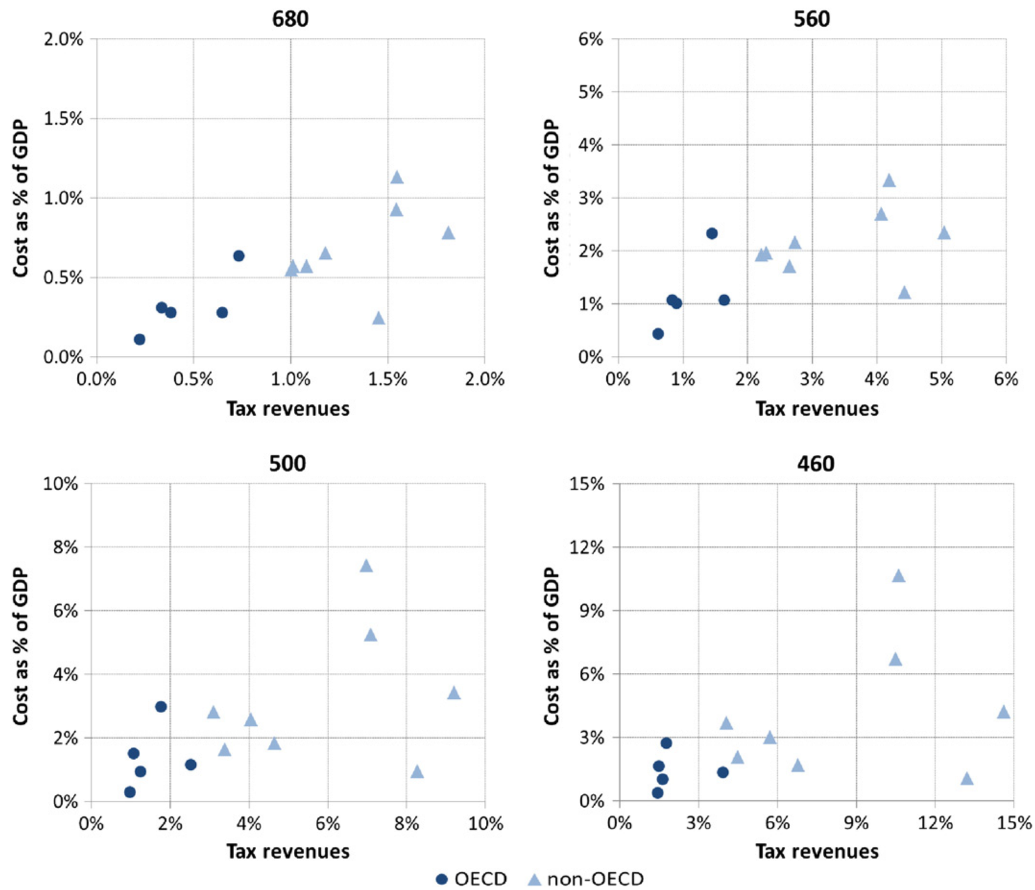

Fig. 4. Relationship between tax revenues and policy cost. Notes: GDP loss calculated as the difference between discounted GDP in the tax scenario and discounted GDP in the Reference scenario, divided by discounted GDP in the Reference scenario; Tax revenues expressed as the ratio of discounted tax revenues for each tax scenario and discounted GDP in the Reference scenario. 5% interest rate used for discounting.

of these two forces varies regionally, intertemporally and depends on the stringency of climate policy (the severity of the carbon tax). The higher is energy intensity in the Reference scenario, the higher is the potential to reduce energy consumption before moving on to expensive options. Typically, energy intensity is higher in developing countries and it is decreasing over time. Therefore, climate policy induces higher investments in the power sector (1) in non-OECD economies, (2) in later years and/or (3) when the carbon price is high. Fig. 5 illustrates these findings.

At the global level, investments in the 680 scenario are always lower than in the Reference scenario. The 560 scenario induces a pattern similar to the Reference scenario until 2035; then investments are higher. The 500 and the 460 scenarios are the most demanding: more investments are needed from 2020 and 2015, respectively.

In energy-efficient OECD economies, investments are higher than in the Reference scenario, with the exception of the 680 scenario until 2045. The demanding 460 and 500 scenarios induce a peak as early as 2040 (460) and 2045 (500). Investments peak and then decline because power plants have a long lifetime: once the optimal capacity is installed, investments are needed only for marginal adjustments and to replace obsolete plants.

In non-OECD economies, carbon taxes promote large energy efficiency improvements and greatly reduce investment needs in power supply. With low carbon taxes, most of the emission reductions until 2050 come from energy efficiency gains. Hence, investments in the power sector are lower than in the Reference scenario (in the 680 scenario always, in the 560 scenario until 2040). The 500 and 460 high tax scenarios induce both energy efficiency and decarbonization. The net effect is a large increase of investments with respect to the Reference scenario. Most of the incremental investments induced by the carbon taxes in the 460, 500 and 560 scenarios in 2050 is in non-OECD countries.

Fig. 6 presents the distribution of investments in the power sector across technologies.[12] In the Reference scenario, coal power plants receive the largest amount of investments: 37% of cumulative investments during the period 2020–2035 and 42% during 2035–2050. Wind power increases its share of total investments from 5% during 2020–2035, on average, to 7% during 2035–2050. Nuclear and hydropower attract instead a declining share of investments: from 25% (2020–2035) to 23% (2035–2050) nuclear and from 20% (2020–2035) to 16% (2035–2050) hydropower. Natural gas attracts a stable 9% of total investments in the power sector. Recent developments in natural gas extraction techniques have the potential to reduced natural gas prices substantially and suggest that natural gas might play a bigger role in power generation than indicated by our scenarios.

With carbon taxes, investments are diverted from coal power generation to IGCC power plants with CCS, nuclear and wind. Cumulative investments in wind power increase between 8% and 48% during 2020–2035 with respect to the Reference scenario and between 15% and 55% during 2035–2050 (lowest value of the interval in 680 scenario and highest in 460 scenario). Cumulative investments in nuclear power increase between 10% and 50% during 2020–2035 and between 25% and 56% during 2035–2050.

In WITCH, solar photovoltaic is not competitive with the other power generation technologies and therefore does not contribute to primary energy supply in any scenario. Backstop technologies have

[12] Hydroelectric power capacity is assumed to be already fully exploited and follows an exogenous dynamic.

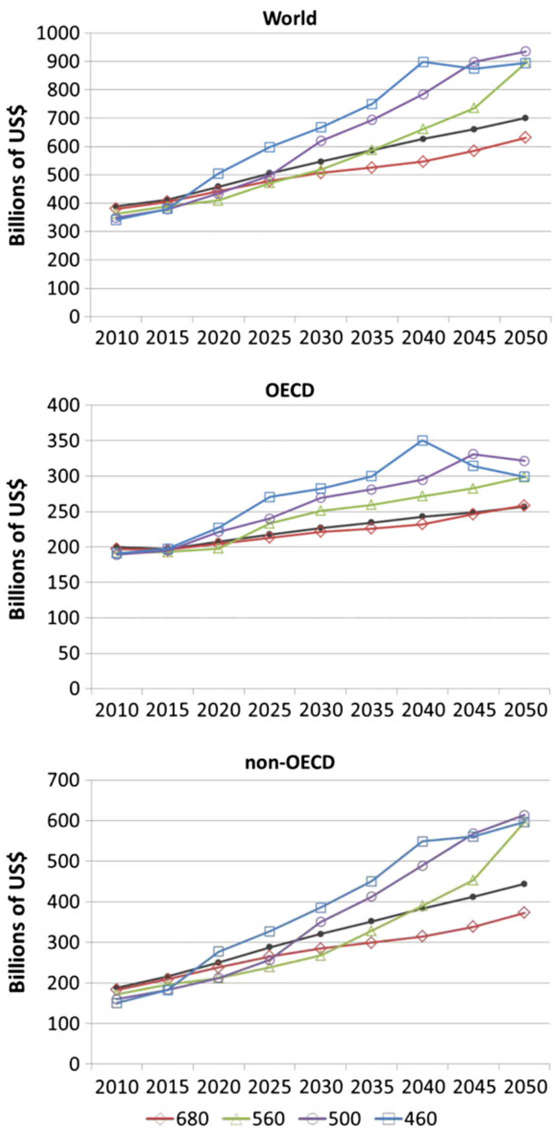

Fig. 5. Total investment in the power sector: World, OECD and non-OECD countries, 2005–2050, not discounted.

no role in the first part of the century. It is important to appreciate that a high penetration of renewables will require investments in new power grids. If new grids will be more expensive than the traditional ones, investments in the power sector will be higher than in our scenarios, which focus only on power generation.[13]

IGCC power plants fuelled by coal and biomass enter the generation mix in all tax scenarios and are the real "game changer" in power generation. In the 460 scenario, investments in IGCC with CCS during the period 2035–2050 amount to 36% of total investments in the power sector, approximately the same share that coal has in the Reference scenario. In absolute terms, IGCC with CCS attracts approximately US$ 4.5 trillion of investments during the period 2035–2050, an average of US$ 300 billion a year (investments in IGCC with CCS are the main driver of the peak that we observe in Fig. 5). Gas with CCS enters the investment mix later than IGCC with CCS, because in our scenario natural gas is more expensive than coal and contains a lower fraction of carbon than coal.

There are two main reasons to explain why IGCC power becomes so important. First, with CCS it is possible to use large and relatively inexpensive coal resources while drastically abating emissions. Second, IGCC power plants with CCS can burn a mix of coal and biomass.[14] When biomass is used together with CCS it is possible to store underground emissions absorbed by the biomass from the atmosphere. This generates "negative emissions" which reduce the stock of CO_2 in the atmosphere and thus reduce global warming.

It is important to note that while a carbon tax penalises emissions, it also rewards the absorption of GHG from the atmosphere by granting a subsidy. A tax system that punishes CO_2 emissions without rewarding net absorption of CO_2 from the atmosphere would not incentivize "negative emission" technologies. Power utility companies would have the incentive to use IGCC power plants with coal and CCS (limited emissions) or IGCC power plants with biomass (zero emissions), but would not use biomass in IGCC power plants with CCS (negative emissions) without a subsidy.

Why would subsidising negative emissions, i.e. carbon dioxide removal, be socially desirable even within a tax-based policy? The reason is that GHGs are a stock pollutant. GHG emissions are not harmful per se. They become harmful when they accumulate in the atmosphere beyond the long-term equilibrium level. Thus, optimality conditions require that the carbon tax reflects the marginal cost of increasing the stock of GHG concentrations in the atmosphere. If the marginal cost of absorbing GHG emissions is lower than the tax, it is then socially optimal to reward the absorption of GHGs. Without carbon dioxide removal the stock of GHGs would be higher than the socially optimal level.

In some regions, very high tax levels create the incentive to absorb more GHGs from the atmosphere than what these regions emit. In this case, subsidies are higher than taxes and should be financed by general taxation. This issue is discussed in Section 7 below.

The new mix of technologies represents a true engineering and managerial challenge. For example, large-scale, worldwide development of CCS has technological, economic and legal risks. The same concerns apply to nuclear. Investors might be required to pay a risk premium on their loans. Since the model assumes a riskless environment, our estimates might underestimate the true demand of investment funds.

While investment needs increase, current expenditures decrease. Investing in nuclear and in wind power reduces sensibly the expenditure for fuels with respect to the Reference scenario: by US$ 19–175 billion/year in the period 2020–2035, and by US$ 74–305 billion/year in the period 2035–2050. Expenditures for operation and maintenance (O&M) decrease with respect to the Reference scenario in the 680 and 560 tax scenarios and increase in the others scenarios, mainly for the relative expansion of nuclear. In all scenarios, the combined expenditure for O&M and fuels decreases with climate policy in the first half of the century.[15] Current expenditures in the power sector are lower than in the Reference scenario even if we include the new annual expenses for CCS. The reduction of current expenditures offsets higher annual investments over the first half of the century in the 680 and 560 scenarios, until 2045 in the 560 scenario and until 2040 in the 2040 scenario.

All our scenarios reveal that the increase of investments in the power sector is accompanied by a sharp contraction of investments in

[13] Massetti and Ricci (2001) introduce investments in "super" grids to distribute concentrated solar power generation in the WITCH model.

[14] Investment cost in integrated gasification combined cycle (IGCC) coal power plants is equal to 3172 US$/kW, 3.0–1.5 times higher than the investment cost used in the model for traditional pulverized coal power plants, depending on the world region. We assume that biomass is used together with coal. In 2015 the amount of biomass cannot exceed 26% of total fuel use. In 2050 the share exogenously grows to 57% and in 2100 biomass can be used alone. The efficiency of IGCC power plants is equal to 0.4 when used only with coal. It is 0.35 if used with biomass only. The capture rate of CCS is equal to 90%. The cost of CCS is region-specific and it increases exponentially as cumulative storage increases. There is not a constraint on storage capacity but in some regions CCS is more costly than in others.

[15] This is true until 2060. After 2060, the 460 scenario will have higher expenditures than the reference scenario, after 2065 (and 2075) also scenario 500 (and 560) will record increasing expenditures comparing to the reference scenario.

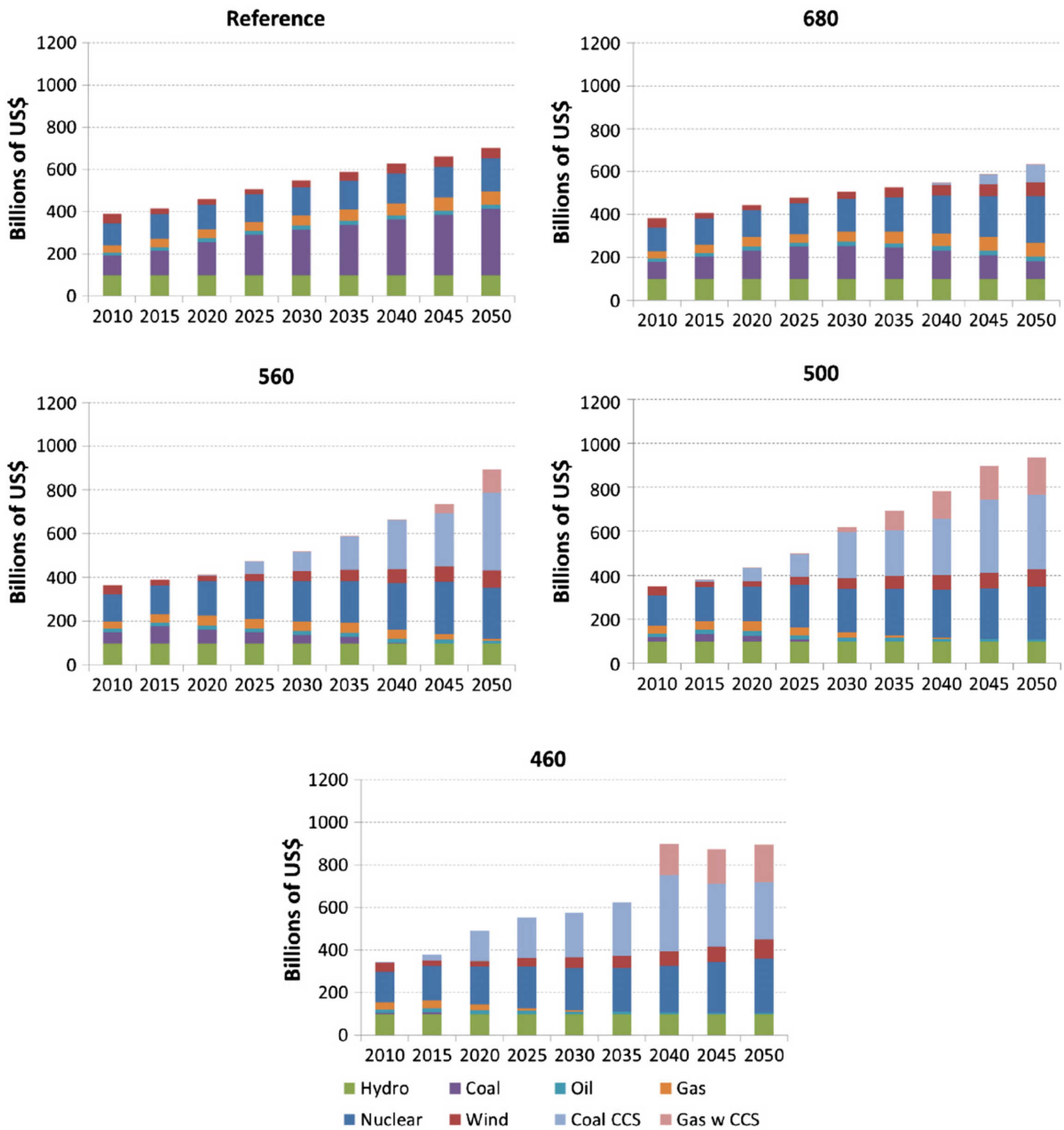

Fig. 6. Total investment in the power sector by generation technology.

other sectors of the economy. Fig. 7 shows the undiscounted average annual variation of investments from 2010 to 2050 in different sectors. The net effect of climate policy is to reduce investments in the economy.

Investments in the oil upstream sector decline in all scenarios because carbon taxes reduce the demand of oil and delay (or make unnecessary) the use of very costly unconventional resources. Investments in unconventional oil are also heavily penalized for high emissions during the extraction process. The model is forward looking and anticipates the heavy toll of carbon taxes on the oil sector after 2050 by reducing investments several decades earlier. The contraction of investments in the oil sector in 2035–2050 is therefore partially explained by high taxes from 2050 onward. In the 680 scenario, oil demand is largely not affected by the carbon tax until 2050. However, investments in oil upstream decline sharply. We cannot assess how investments in coal and in gas extraction change. Since consumption of all fossil fuels declines, we expect that investments in coal and in gas will also decline and our conclusions would be reinforced.

Climate policy indirectly affects investments in all sectors. Higher energy costs create incentives to substitute capital and labour inputs to energy—i.e. to increase energy efficiency. However this is not a free lunch. As explained in Section 2, there is empirical evidence to argue that the elasticity of substitution between energy on one side and capital and labour on the other side is low, with several studies indicating that it is lower than one. The model is calibrated using an elasticity of substitution equal to 0.5. Therefore, substituting capital and labour for energy causes a loss of productivity. The marginal product of capital decreases and it induces a lower level of investments and lower aggregate output. Fig. 7 shows that the absolute contraction of investments in the aggregate production good of our Ramsey-type economy (labelled as “investment in all other sectors”) is large in all scenarios.

The contraction of the oil sector and the shift from energy to capital and labour explain why investments in the aggregate production good increase with respect to the Reference scenario in the 560, 500 and 460 scenarios (Fig. 8, panel a). The share of total investments that goes to the power sector decreases with respect to the Reference

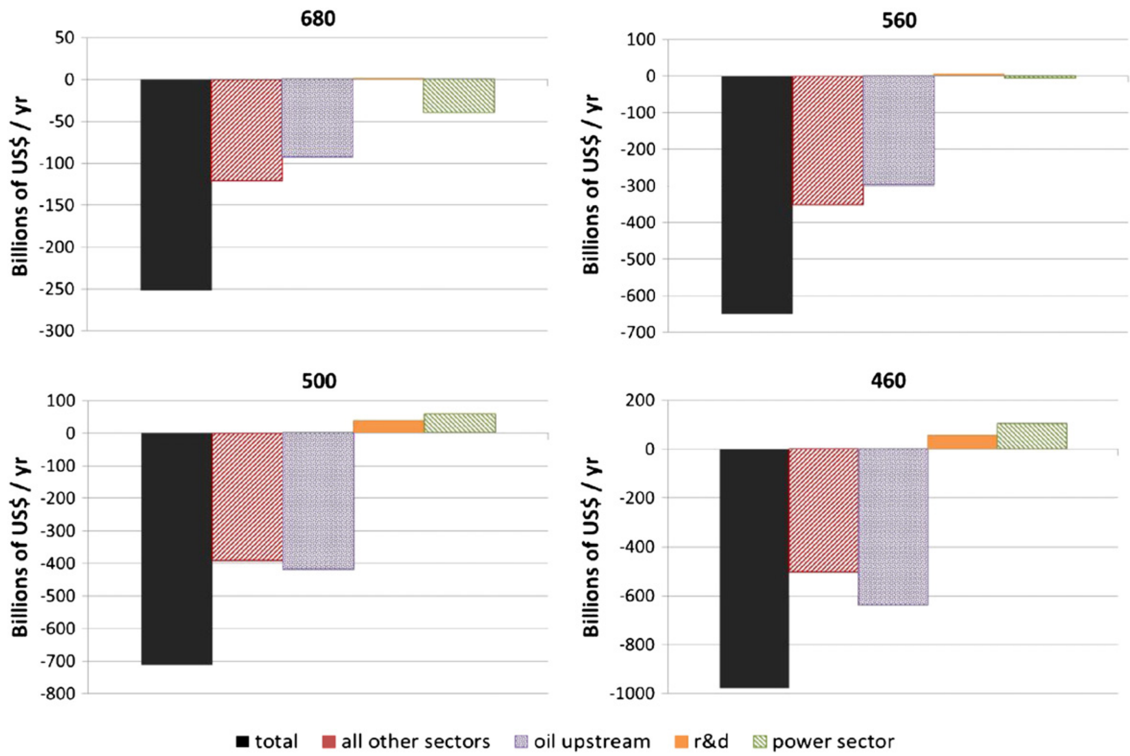

Fig. 7. Change of annual global investments with respect to the Reference scenario, average from 2010 to 2050. Notes: Global average annual investments between 2010 and 2050 are equal to US$ 20.1 trillion (Reference), US$ 19.9 trillion (680), US$ 19.5 trillion (560), US$ 19.4 trillion (500), and US$ 19.2 trillion (460).

scenarios in the 680 scenario from 3.5% to 2.0% while it remains fairly stable in the other scenarios.

6. Investments in innovation

A key component of the optimal response to a carbon tax is innovation. WITCH endogenously determines the technological frontier in three sectors: aggregate end-use energy efficiency, a power sector backstop technology and a backstop substitute for oil in final consumption. Investments in energy efficiency R&D increase the stock of energy-related knowledge, which enhances the productivity of final energy in end uses. Investments in backstop R&D increase a sector-specific knowledge stock that enters a two-factor learning curve and reduce the cost of backstop power plants and/or the cost of the backstop fuel. If nuclear, CCS and wind are available without constraints, as in all scenarios under exam, the model shows that it is not necessary to invest in a backstop power generation technology. Hence, R&D investments are directed only to increase energy efficiency and to develop a backstop fuel to substitute final oil consumption.

In the Reference scenario, investments in R&D are equal to about 0.02% of GWP in 2020 and then slowly decline in relative terms, following the trend of the past 20 years (Fig. 9). It is not optimal to invest in backstop low carbon technologies in the Reference scenario. The 680 and 560 scenarios induce only a small increase of investments in energy efficiency R&D. The 460 and 500 scenarios trigger instead a sharp increment of investments in energy efficiency and a wave of new investments to lower the cost of the backstop zero carbon fuel technology. The model anticipates the high value of the new carbon-free fuel and starts accumulating knowledge as soon as possible. Annual investments in backstop technology during the period 2035–2050 are equal, on average, to US$ 33.5 billion and US$56.7 billion in the 500 ad 460 scenarios, respectively. During 2035–2050 they increase to an annual average of US$ 53.5 billion (500) and US$ 64.3 billion (460). In all scenarios, but especially in the 460 scenario, investments start in 2010, before the tax is introduced. However, as the new fuel is developed, investments keep rising at a constant pace but decline as percentage of GDP: once the new backstop technology becomes competitive, only marginal adjustments to ongoing R&D investments are needed (see Bosetti et al., 2011).

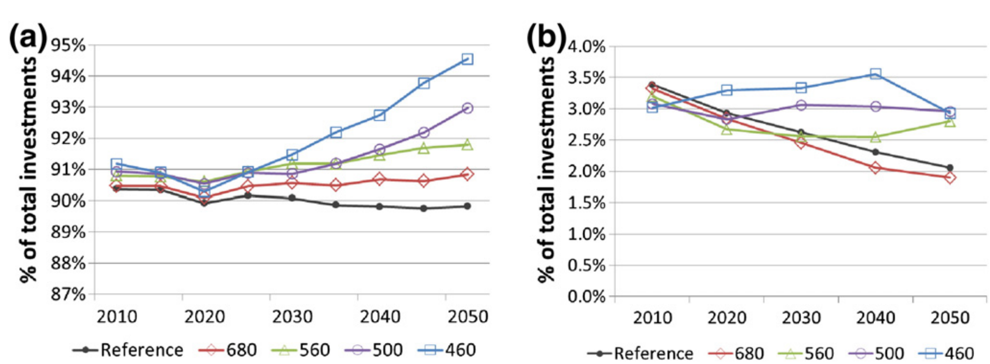

Fig. 8. Investments in all other sectors (a) and investments in the power sector (b) as share of total investments.

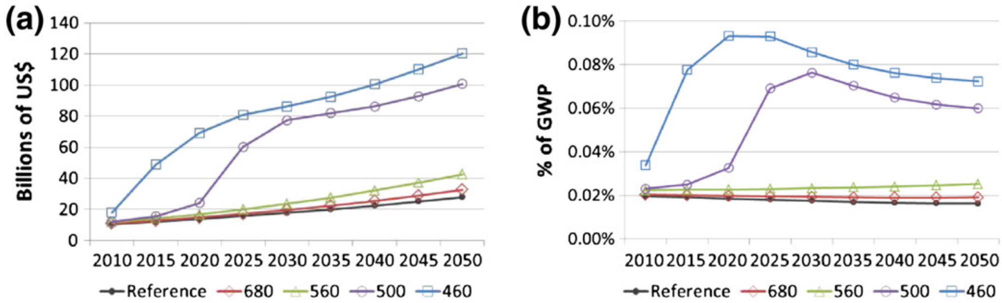

Fig. 9. Global investments in energy-related innovation in (a) billions of US$ and (b) as percentage of GWP.

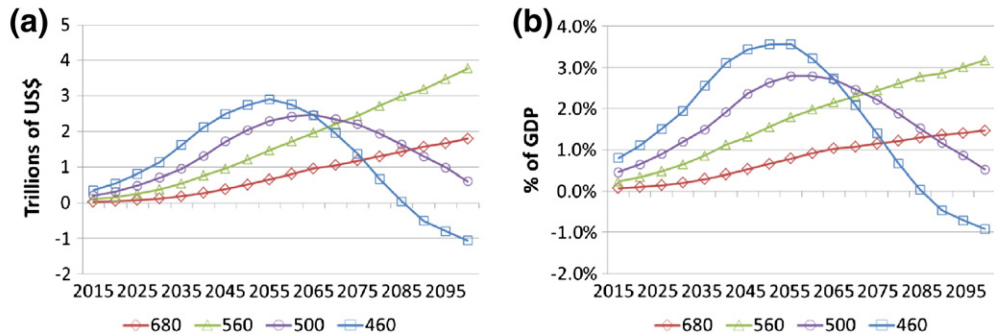

Fig. 10. Revenues from carbon taxes in OECD economies in absolute value (a) and as a fraction of GDP (b).

Our scenarios show that the optimal investment in R&D may be modest if compared to aggregate investments. However, the fast expansion suggested by the model may represent a challenge for both firms and governments. However, vast amounts of resources have already been effectively mobilized to finance ambitious technological advancements in a short period of time. For example, in the 1960s the Apollo Space Programme of NASA required investments comparable to what the model shows it is optimal to do in the USA in the high tax scenarios. NASA spent approximately US$ 94 billion in 13 years to send a man on the moon (in 2005 US$). During the peak year of funding NASA spent about 0.4% of GDP in the Apollo Programme (Stine 2009) which is much less than what our scenarios show. In the most stringent scenario (460) the R&D investments in the USA peak in 2015 at 0.13% of GDP.

7. Carbon tax revenues

The four climate policy scenarios examined in the previous sections reveal that carbon taxes generate substantial fiscal revenues in OECD economies.[16] The amount of the revenues depends on the level of the tax and on the tax base: they vary from a minimum of US$ 31 billion in 2015 for the 560 scenario to US$ 3.8 trillion in 2100 for the 560 scenario (Fig. 10a). In terms of GDP, tax revenues vary from a fraction of percentage point to 3.6% in 2055 for the 460 scenario (Fig. 10b). In this latter scenario, fiscal revenues from carbon taxes are comparable to major fiscal revenues and major government expenditures. For example, social security contributions are equal to about 9% of GDP in OECD economies. The expenditure for pensions is equal to about 8% of GDP OECD (2011).

In the 500 and 460 scenarios, revenues first increase and then decrease, as in a "carbon Laffer" curve. We do not find instead a peak of revenues for the 560 and 680 scenarios. The 560 scenario collects the highest tax revenues (US$ 151.5 trillion). The 500 scenario follows with US$ 129 trillion, the 460 scenarios with US$ 108 trillion and the 680 scenario with US$ 70 trillion. Thus, the "carbon Laffer" curve holds also across different tax scenarios.

At the end of the century, in the 460 scenario, OECD countries as a whole find it optimal to invest in carbon dioxide removal. As explained in Section 4, the tax becomes a subsidy when applied to absorbed emissions. The subsidy is financed by a lump-sum contraction of consumption and investments, mirroring the lump-sum rebate of the carbon tax. In the real world, governments would need to increase fiscal pressure or to reduce public expenditures to finance a net absorption of GHGs. In OECD countries, governments would either increase taxation or reduce other expenditures for an amount equal to US$ 1.1 trillion/year, or 0.9% of GDP, at the end of the century.

For the 460 scenario we provide a regional outlook in Fig. 11. The highest tax revenues, measured in relation to GDP, are observed in regions with high marginal abatement costs and/or scarce biomass resources. Tax revenues follow a "carbon Laffer" curve in OECD regions. The peak is in 2040 for KOSAU, in 2050 for the USA, in 2055 for EEURO and 2060 WEURO. KOSAU, CAJAZ and the USA receive positive carbon tax revenues until 2060, 2070 and 2080, respectively. WEURO and EEURO always have net positive tax revenues: EEURO has high marginal abatement costs, while WEURO has low biomass potential according to the GLOBIOM model. Among non-OECD economies, poor (SSA and SASIA) and very carbon intensive regions (MENA and TE) have very high carbon tax revenues in relation to their GDP. The elasticity of emissions to the carbon tax is lower than in OECD countries due to relatively higher carbon intensity of output and to higher emissions in the Reference scenario. Carbon tax revenues peak between 2040 and 2075 in non-OECD regions. In China and in India tax revenues reach a plateau and remain close to 10% of GDP until the end of the century. LACA, with abundant biomass resources is the only non-OECD region that pays net subsidies from 2070.[17]

Fig. 11 shows that carbon tax revenues are very high in developing countries and in resource-based economies. By aggregating several countries in one large region and by aggregating over time we actually provide a downward-biased scenario of the highest possible carbon

[16] Auctioning of emissions permits would generate the same revenue.

[17] WITCH is calibrated in the base year using market exchange rates. The use of purchasing power parities would reduce the initial carbon intensity of the economy and possibly reduce carbon tax revenues in relation to GDP.

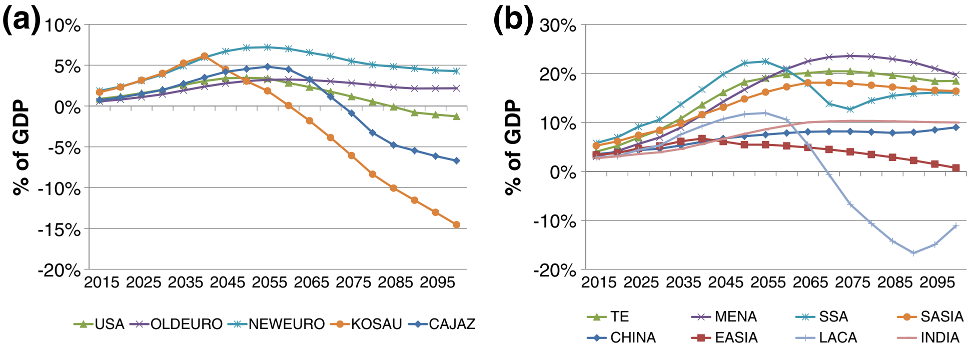

Fig. 11. Revenues from carbon taxes in (a) OECD and (b) non-OECD countries, in the 460 scenario. Notes: WEURO: Western Europe; EEURO: Eastern Europe; KOSAU: Australia, South Africa and South Korea; CAJAZ: Canada, Japan and New Zealand; TE: Transition Economies; MENA: Middle East and Northern Africa; SSA: Sub-Saharan Africa; SASIA: South Asia; EASIA: East Asia; LACA: Latin America and the Caribbean. Revenues net of expenses for subsidies to biomass with CCS.

tax burden in each country in any year. The political and economic feasibility of implementing such large taxation schemes, even if taxes are recycled within the economy, is at least questionable. Many countries might not be able to manage huge carbon tax revenues in an efficient, effective and sustainable way. Tol (2012) raises similar concerns and argues that high carbon taxes in the short-term might not be politically feasible, because they would generate revenues higher than the all present tax incomes in many poor or highly carbon intensive economies. Our analysis confirms that this is a problem in the short run and it argues that it worsens considerably over time.

Aggregate tax revenues illustrated in Fig. 10 and in Fig. 11 are net of the subsidy that goes to biomass electricity generation. Fig. 12 illustrates the flow of taxes out of the power sector and the flow of subsidies into the power sector, in OECD economies. With the exception of the 680 scenario, the power sector becomes a net recipient of subsidies. In the 460 scenario the power sector does not provide carbon tax revenues after 2055, in the 500 scenario, after 2060 and after 2065 in the 560 scenario. In 2050, for the 460 scenario, IGCC power plants that use biomass with CCS would receive about 0.4 US$/kWh as subsidy; in 2100 about 2 US$/kWh. However, it is important to note that the subsidies will not necessarily become rents for the power sector. The biomass resource owner or the owner of the geological deposits for sequestered carbon might well get most of the subsidy.

8. Conclusions

The Integrated Assessment Modeling community has been prolific in providing estimates of the macroeconomic costs of climate policy, but has virtually neglected investment needs and the distribution of investments over regions, sectors and time. This is however a crucial information to assess the finance side of climate policy. This paper aims at filling this gap in the literature by providing a detailed assessment of investment needs in four representative carbon tax scenarios generated using the Integrated Assessment Model WITCH. Our main findings can be summarised as follows.

In our analysis, the transition to a green, low carbon, economy is induced by global carbon taxation. As a reaction to climate policy, global investments in the power sector increase only in the 500 ppm and 460 ppm stabilisation scenarios during the first half of the century. In the 680 ppm and 560 ppm scenarios, global investments in the power sector decline because electricity demand shrinks due to strong efficiency gains induced by climate policy. The higher cost of low- or zero-emission power generation technologies is offset by a contraction of installed capacity. Most interestingly, we find that for mid-range stabilisation targets, investments in the power sector would remain unaltered with respect to the Reference scenario while GDP would decline. Investments in the power sector are more elastic to carbon pricing than aggregate output. In the highest tax scenario, cumulative discounted investments in the power sector over 2010–2050 increase by 10% with respect to the Reference scenario, while over the same time period costs are approximately equal to 1.3%.

In our four scenarios, climate policy reduces investments in the generic capital goods, which is used, together with labour and energy, to produce the consumption good of the various economies. Substituting capital and labour for energy reduces productivity and induces a contraction of the optimal investment level. Investments in oil upstream also decline substantially, depressing further the level of investments in the economy. Investments in R&D increase in all scenarios and show a remarkable expansion in the 500 and 460 scenarios. However, investments in R&D continue to attract a fairly small share of GDP even in the high tax scenarios. Therefore, total investments decline in all scenarios.

Financial resources shift to the public sector. Global tax revenues are indeed high, both in absolute and relative terms. Interestingly,

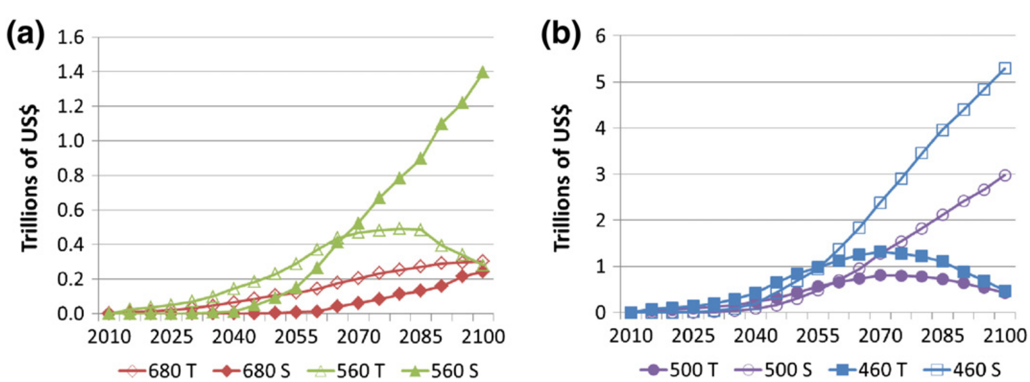

Fig. 12. Tax revenues and subsidies to the power sector in OECD economies, for low carbon tax scenarios (a) and high carbon tax scenarios (b). Notes: 680 T illustrates taxes from the power sector; 680 S illustrates subsidies to the power sector for the scenario 680. The same for all other scenarios.

tax revenues follow a "carbon" Laffer curve, first increasing and then decreasing with the level of taxation. Therefore, cumulative tax revenues are the highest with the mid-range 560 tax scenario. In 2100, tax income reaches US$ 3.8 trillion in the 560 scenario. In terms of GDP, tax revenues vary from a fraction of percentage point to 3.8% of GDP in the 460 scenario.

In all scenarios, when taxes are sufficiently high, it becomes optimal to remove GHGs from the atmosphere by subsidising IGCC power plants with CCS. In the highest tax scenario, some regions absorb more GHGs that they emit. Hence, governments would need to increase fiscal pressure or to reduce public expenditures to finance a net absorption of GHGs.

Carbon tax revenues are very high (up to 20% of GDP) in developing countries and in resource-based economies. The political and economic feasibility of implementing such large taxation schemes, even if taxes are recycled within the economy, is at least questionable. Many countries might not be able to manage huge carbon tax revenues in an efficient, effective and sustainable way.

The above results can be useful to assess the finance implications of climate policy. Policy makers and the business community are indeed increasingly interested in receiving information on the costs and financial needs of the transition to a green economy. Macroeconomic costs and/or technological changes do not constitute a sufficient information. The amount of resources to be invested and those collected by the public sector and then recycled, the distribution of investments over sectors, regions and time are all important information to better understand the economic implications of climate policy.

Appendix A

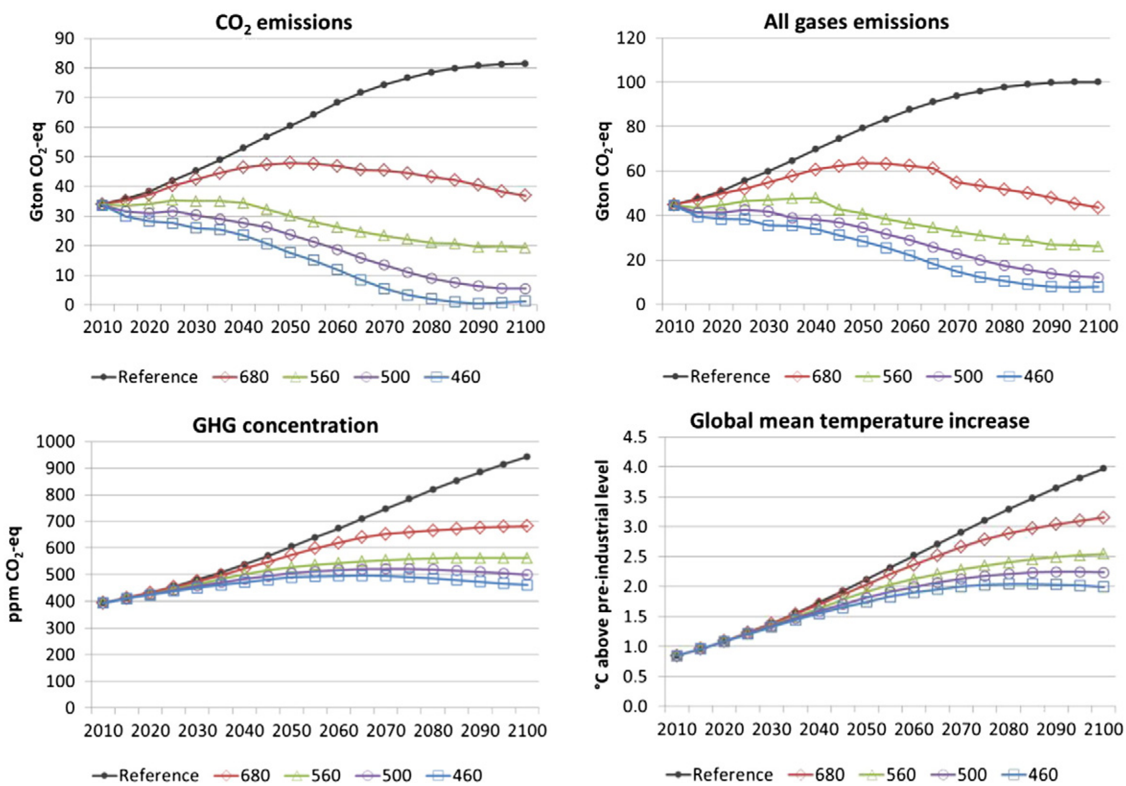

Fig. A1. Emissions, concentration of GHG and global mean temperature increase above pre-industrial level. Notes: CO_2 emissions include emissions from Land Use, Land Use and Change and are net of carbon capture and sequestration. All gases emissions include CO_2 emissions and emissions of methane (CH_4), nitrous oxide (N_2O), short-lived fluorinated gases (i.e. HFC with lifetimes under 100 years) and long-lived fluorinated gases, (i.e. HFC with long lifetime, PFCs and SF_6). Radiative forcing in 2100 is equal to 4.8, 3.8, 3.2 and 2.8 W/m^2.

References

Barker, Terry, Bashmakov, Igor, Alharthi, Awwad, Amann, Markus, Cifuentes, Luis, Drexhage, John, Duan, Maosheng, 2007. "Mitigation from a Cross-sectoral Perspective." In Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., et al. (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. WITCH: a World Induced Technical Change Hybrid model. Energy J. 27 (1), 13.

Bosetti, V., De Cian, Enrica, Sgobbi, A., Tavoni, M., 2009a. The 2008 WITCH model: new model features and baseline. FEEM Note Di Lav. 85.

Bosetti, V., Massetti, E., Tavoni, M., 2007. The WITCH model. structure, baseline, solutions. FEEM Note Di Lav. 10.

Bosetti, Valentina, Carraro, Carlo, Duval, Romain, Tavoni, Massimo, 2011. What should we expect from innovation? A model-based assessment of the environmental and mitigation cost implications of climate-related R&D. Energy Econ. 33 (6), 1313–1320. http://dx.doi.org/10.1016/j.eneco.2011.02.010 (November).

Bosetti, Valentina, Carraro, Carlo, Massetti, Emanuele, 2009b. Banking permits: economic efficiency and distributional effects. J. Policy Model 31 (3), 382–403. http://dx.doi.org/10.1016/j.jpolmod.2008.12.005 (May).

Bosetti, Valentina, Longden, Thomas, 2012. Light duty vehicle transportation and global climate policy: the importance of electric drive vehicles. FEEM Note di Lav. (011).

Calvin, Katherine, Leon Clarke, Volker Krey, Geoffrey Blanford, Jiang Kejun, Mikiko Kainuma, Elmar Kriegler, Gunnar Luderer, and P.R. Shukla. (forthcoming). "The role of Asia in mitigating climate change: results from the Asia modeling exercise." Energy Economics.

Clarke, Leon, Edmonds, Jae, Krey, Volker, Richels, Richard, Rose, Steven, Tavoni, Massimo, 2009. International climate policy architectures: overview of the EMF 22 international scenarios. Energy Econ. 31 (Supplement 2), S64–S81. http://dx.doi.org/10.1016/j.eneco.2009.10.013 (0) (December).

Edenhofer, Ottmar, Carraro, Carlo, Hourcade, Jean-Charles, Neuhoff, Karsten, Flachsland, Christian, Jakob, Michael, Popp, Alexander, et al., 2009. "RECIPE: The Economics of

Decarbonization". Potsdam Institute for Climate Impact Research. http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/research-act-intl-climate-pol/recipe-groupspace/working-papers/recipe-synthesis-report/.
Edenhofer, Ottmar, Knopf, Brigitte, Barker, Terry, Baumstark, Lavinia, Bellevrat, Elie, Chateau, Bertrand, Criqui, Patrick, et al., 2010. The economics of low stabilization: model comparison of mitigation strategies and costs. Energy J. 31, 11–48.
Edenhofer, Ottmar, Pichs-Madruga, Ramón, Sokona, Youba, Seyboth, Kristin, Kadner, Susanne, Zwickel, Timm, Eickemeier, Patrick, et al., 2011. Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Forster, P., Ramaswamy, P., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., et al. (Eds.), In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New Your, NY, USA.
Haites, Erik, 2011. Climate change finance. Clim. Pol. 11 (3), 963–969.
Havlík, P., Schneider, U.A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Blok, K., et al., 2011. Global land-use implications of first and second generation biofuel targets. Energy Pol. 39 (10), 5690–5702. http://dx.doi.org/10.1016/j.enpol.2010.03.030 (October).
IEA, 2010. "World Energy Outlook 2010". International Energy Agency. http://www.iea.org/weo/2010.asp.
IEA, 2011. World Energy Outlook 2011. OECD/IEA, Paris, France.
Massetti, Emanuele, Ricci, Elena C., 2001. Super-grids and concentrated solar power: a scenario analysis with the WITCH model. FEEM Note Di Lav. 47. http://www.feem.it/userfiles/attach/201111171230204NDL2011-047.pdf.
Massetti, Emanuele, Sferra, Fabio, 2010. A numerical analysis of optimal extraction and trade of oil under climate and R&D policy. FEEM Note Di Lav. 113.
Nordhaus, William D., Yang, Zili, 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. Am. Econ. Rev. 86 (4), 741–765.
OECD, 2011. Revenue Statistics 2011. OECD Publishing. http://dx.doi.org/10.1787/rev_stats-2011-en-fr.OECD. 2011. *Revenue Statistics 2011*. OECD Publishing. http://dx.doi.org/10.1787/rev_stats-2011-en-fr.
Riahi, Keywan, Dentener, Frank, Gielen, Dolf, Grubler, Arnulf, Jewell, Jessica, Klimont, Zbigniew, Krey, Volker, McCollum, David, Pachauri, Shonali, Rao, Shilpa, Ruijven, Bas vn, van Vuuren, Detlef P., Wilson, Charlie, 2012. Energy pathways for sustainable development. In Global Energy Assessment: Toward a Sustainable Future, in GEA, 2012: Global Energy Assessment—Toward a Sustainable Future. : International Institute for Applied Systems AnalysisVienna, Austria and Cambridge University Press, Cambridge, UK and New York, NY, USA.
Stine, D.D., 2009. The Manhattan Project, the Apollo Program, and Federal Energy Technology R&D Programs: A Comparative Analysis. Specialist in Science and Technology Policy, Congressional Research Service.
Tol, Richard, 2012. Leviathan carbon taxes in the short run. Clim. Chang. 114 (2), 409–415. http://dx.doi.org/10.1007/s10584-012-0544-z.