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Energy and climate change in China

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ABSTRACT. This paper examines future energy and emissions scenarios in China generated by the Integrated Assessment Model WITCH. A Business-as-Usual scenario is compared with five scenarios in which greenhouse gases emissions are taxed, at different levels. The elasticity of China's emissions is estimated by pooling observations from all scenarios and comparing them with the elasticity of emissions in OECD countries. China has a higher elasticity than the OECD for a carbon tax lower than US$50 per ton of CO_2-eq. For higher taxes, emissions in OECD economies are more elastic than in China. Our best guess indicates that China would need to introduce a tax equal to about US$750 per ton of CO_2-eq in 2050 to achieve the Major Economies Forum goal set for mid-century. In our preferred estimates, the discounted cost of following the 2°C trajectory is equal to 5.4 per cent and to 2.7 per cent of GDP in China and the OECD, respectively.

1. Introduction

The economic growth of China has been impressive in recent years. This growth has been fuelled by a rapid industrial expansion and it has caused an ever-growing appetite for natural resources in general and energy in particular, with worldwide implications. China's share of global Gross

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Domestic Product (GDP) in 2005 was roughly 5 per cent. Its share of global Total Primary Energy Supply (TPES) was much higher: 17 per cent. Its share of global emissions of carbon dioxide (CO_2), the most important among all greenhouse gases (GHG), was 22 per cent in 2005.[1] This indicates that China has high energy intensity of input and even higher carbon intensity of energy with respect to the world average. This combination of forces – high economic growth with high energy and carbon intensity – turned China into the world's leading CO_2 emitter in 2006, five to nine years earlier than what had been forecasted as recently as in 2004.

Future prospects for the Chinese economy look bright. Home to one-fifth of the world population, China has the potential to become a global economic giant. The road to prosperity is, however, still very long because China's GDP per capita is only one-fourth of the world average. Such a prolonged period of high economic growth has the potential to multiply China's carbon emissions by a factor of two or three, even if we account for massive improvements in energy efficiency.

For its present and future share of global CO_2 emissions China must therefore be a key player in action against global warming. However – understandably – China is not willing to accept any absolute target, like many other developing and developed economies. In the United Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) held in Copenhagen in December 2009, China made a step forward, pledging to reduce the GHG emissions intensity of its economy by 40–45 per cent with respect to 2005 in 2020. This target leaves broad flexibility to the Chinese authorities and it fits well into a renewed domestic plan of action to increase energy efficiency: domestic motivations seem still to prevail over concerns for the protection of the global public good.

This study presents long-term scenarios of energy demand and composition, emissions and the economy, produced using the World Induced Technical Change Hybrid (WITCH) model (http://www.witchmodel.org), which is an Integrated Assessment Model. WITCH is a Ramsey-type neoclassical optimal growth model with a detailed description of the energy sector. A game-theoretic structure governs the interaction of 13 regions of the world.

A first scenario of energy demand and composition is derived under the assumption that no action is taken to reduce GHG emissions. We refer to this scenario as the Business-as-Usual (BaU). A second set of scenarios studies the transformations induced by a tax on GHG emissions. Five scenarios will explore the implications of carbon pricing on GHG emissions, on carbon intensity of energy and energy intensity of GDP, on power generation technologies, and on the macroeconomic cost of the five stylized climate policy scenarios.

Among the many studies that have generated long-term energy and emissions outlook for China using energy-economy models, we signal Jiang and Hu (2006), Cai *et al*. (2008), ERI (2009), IEA (2007, 2010) and Zhou *et al*. (2011). With respect to these studies we expand the time horizon

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[1] Data on China from the World Bank Development Indicators.

beyond 2050, we consider a wide range of carbon prices that span all the climate policy targets now under discussion and we use a model that has a solid macroeconomic foundation and complex international interactions. We do not have instead a detailed description of end-use technologies and non-electric energy demand, which might overstate marginal abatement costs in those sectors. Blanford *et al*. (2008) generate long-term scenarios for China using MERGE, a model that shares many similarities with WITCH. They make an interesting analysis of energy intensity dynamics and assess the role of China in two scenarios that stabilize global GHG concentrations at 550 ppme and 450 ppme in 2100. Earlier studies include Kram *et al*. (2000) and van Vuuren *et al*. (2003), who use SRES scenarios to derive alternative technological and emission trajectories for China.

Scenarios developed by IAMs are most informative when used for comparative analysis. The large set of carbon prices that we use allows us to test the elasticity of the Chinese economy and energy system under a wide range of policy regimes. Throughout the paper we also compare China to OECD economies. Although still a developing country, China can be compared to other developed economies when it comes to the size of the economy, of emissions and of energy demand. This enables us to get deeper insights into the Chinese reactiveness to carbon taxes and to make judgements on the political acceptability of several policy targets that are debated in the policy arena. In another paper we compare China to India, using four tax scenarios generated using an older version of the model (Massetti, 2011).

As this article goes to press, a new set of scenarios generated by the Asia Modelling Exercise (AME) – which involved about 20 IAMs – becomes available (Calvin *et al*., 2012). In our article we use the same model used for the AME exercise and the same set of carbon tax scenarios. It is therefore possible to compare our article to this new large body of literature. In the AME, WITCH was used to study a hypothetical developing Asia Emission Trading scheme, in which China becomes a regional leader in climate change mitigation policy (Massetti and Tavoni, 2012).

The rest of the paper is structured as follows: section 2 introduces the reader to historic data and to the BaU scenario, and also contains a brief overview of the WITCH model. Section 3 presents the five climate policy scenarios. Conclusions follow in section 4 with several remarks on a realistic climate policy pattern for China. The online appendix displays detailed information on the optimal energy mix in the BaU and in the five policy scenarios.

2. Historic data and the BaU scenario

Table 1 synthetically displays key data on the economy, on the energy system, on CO_2 emissions and on key efficiency indicators from 1960 to 2100. Historic data (1960–1990) has been gathered from a variety of sources by the World Bank in its Development Indicators series. Future scenarios are produced using the latest version of the WITCH model (Bosetti *et al*., 2006, 2007, 2009b; http://www.witchmodel.org).

Table 1. *Historic data and future scenario on the economy, energy system and emissions*

	Historic data		*WITCH BaU scenario*					*Historic data*		*WITCH BaU scenario*			
	1970	***1990***	***2010***	***2030***	***2050***	***2100***		***1970***	***1990***	***2010***	***2030***	***2050***	***2100***
			The Economy							***CO_2 Emissions***			
GDP (trillion \$)							***CO_2 emissions(Gt)***						
China	0.1	0.4	3.7	15.2	31.9	57.6	China	0.8	2.5	6.8	12.6	17.9	20.9
OECD	9.7	19.5	39.8	59.0	78.9	124.3	OECD	9.2	11.0	13.1	14.5	17.0	19.9
World	11.8	24.3	53.2	102.4	173.4	361.0	World	14.9	22.6	29.0	42.7	59.2	80.2
GDP per capita ('000 \$)							***CO_2 emissions per capita (metric tons)***						
China	122	392	2,718	10,324	22,477	47,913	China	0.9	2.2	5.0	8.6	12.6	17.4
OECD	12,290	21,388	35,914	50,589	67,228	113,408	OECD	11.6	12.0	11.9	12.5	14.5	18.1
World	3,200	4,613	7,712	12,320	18,868	39,632	World	4.0	4.3	4.2	5.1	6.4	8.8
GDP Growth rate (%, average yearly rate)							***Population, total (millions)***						
China	–	7.7	11.2	7.3	3.8	1.2	China	818	1,135	1,359	1,467	1,418	1,202
OECD	–	3.5	3.6	2.0	1.5	0.9	OECD	793	914	1,108	1,165	1,173	1,096
World	–	3.7	4.0	3.3	2.7	1.5	World	3,685	5,272	6,904	8,315	9,188	9,110
			The Energy System							***Efficiency Indicators***			
Energy use (Mtoe)							***Carbon Intensity of Energy (t of CO_2 per Mt of oil equivalent)***						
China	–	863	1,955	3,659	5,113	5,620	China	–	2.85	3.48	3.44	3.50	3.71
OECD	3,241	4,333	5,006	5,556	6,039	6,189	OECD	2.83	2.53	2.63	2.61	2.81	3.21
World	–	8,574	10,636	15,034	19,565	23,957	World	–	2.63	2.73	2.84	3.02	3.35

Energy use per capita (toe)							***Energy Intensity of GDP (t of oil eq. / '000 $)***						
China	–	0.8	1.4	2.5	3.6	4.7	China	–	1.94	0.53	0.24	0.16	0.10
OECD	4.1	4.7	4.5	4.8	5.1	5.6	OECD	0.33	0.22	0.13	0.09	0.08	0.05
World	–	1.6	1.5	1.8	2.1	2.6	World	–	0.35	0.20	0.15	0.11	0.07
Fossil fuels energy consumption (%of total)							***Carbon Intensity of GDP (t of CO_2-eq / '000 $)***						
China	–	75	85	90	92	91	China	–	5.53	1.84	0.83	0.56	0.36
OECD	95	84	90	88	86	80	OECD	0.94	0.56	0.33	0.25	0.22	0.16
World	95	81	86	87	88	86	World	–	0.93	0.54	0.42	0.34	0.22

Notes: 1970 and 1990 data aggregated by the World Bank Development Indicators. Fossil fuel comprises coal, oil, petroleum and natural gas products. (*Source*: International Energy Agency.) Energy use refers to use of primary energy before transformation to other end-use fuels. (*Source*: International Energy Agency.) CO_2 emissions are those stemming from the burning of fossil fuels and the manufacture of cement. (*Source*: Carbon Dioxide Information Analysis Center (CDIAC).) GDP at purchaser's prices data are in constant 2000 US$. Dollar figures for GDP are converted from domestic currencies using 2000 official exchange rates. (*Source*: World Bank national accounts data and OECD National Accounts data files.) Population data is from a variety of sources, mid-year estimates. 2010–2100 data are from the WITCH model BaU scenario.

WITCH is an IAM with endogenous technical change in the energy sector at its core. The economy evolves along the lines of a Ramsey–Cass–Koopmans optimal growth framework. Thanks to a synthetic description of end-use and energy sector technologies it is possible to reduce the degree of complexity and to focus on key technological transformations: fuel switching, energy efficiency, cost reductions in existing technologies and R&D investments to foster innovation.

A second peculiarity of WITCH is a characterization of the non-cooperative interaction of world regions – on global climate, technology and natural resources – by means of an open-loop Nash game, as in the Rice model (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000). International R&D spillovers and global learning connect the technological frontier of all regions in this non-cooperative framework (Bosetti *et al.*, 2008).

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. The model relies on estimates for reference emissions, and a top-down approach for mitigation supply curves for non-CO_2 gases and for LULUCF emissions. The patter of aerosols is exogenous.

The latest version of the model that we use includes the separation of wind and solar power, endogenous investments in oil upstream and endogenous trade of oil, bioenergy with carbon capture and sequestration (BECCS) together with other minor improvements and a revised BaU scenario.[2]

The Chinese economy has expanded at remarkably high rates during the past 30 years. From 1970 to 1990 China's GDP grew at an average rate of 7.7 per cent per year. From 1990 to 2010 the expansion of the economy was even faster, with an average growth rate of 10.5 per cent according to the latest estimates of 2010 GDP by the World Bank.[3] From 2010 to 2030 the average yearly growth rate is still high in the BaU scenario, while it progressively declines to reach present level growth rates of OECD economies between 2030 and 2050. In the second half of the century, in

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[2] Solar power is described as a backstop technology whose cost follows a two-factor learning curve. The cost of wind electricity is defined by four components: depletion and learning, spinning reserve, backup capacity, and discarded electricity. As the best sites get exhausted the cost of wind power increases. However, learning-by-doing endogenously reduces the investment cost. The cost of the biomass feedstock is determined by WITCH on the basis of regional supply cost curves obtained by the land use GLOBIOM model (Havlík *et al.*, 2010). GLOBIOM accounts for residual emissions associated with the full life cycle of growing, harvesting and transporting the biomass. Investments in oil upstream are endogenous (Massetti and Sferra, 2010). Further documentation is available from the authors on request.

[3] Our BaU scenario shows a slightly higher growth rate because it does not include the effects of the global economic crisis.

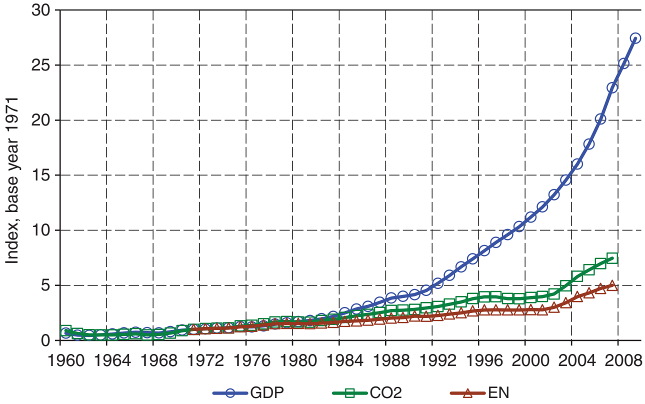

Figure 1. *Long-term time series of GDP, CO_2 emissions and energy use*
Source: See notes to table 1. Base year 1971.

our BaU scenario, China still grows faster than other OECD economies but slower than the world average. Economic growth has fuelled an unprecedented improvement in the standard of life during the past 40 years in China. Average GDP per capita increased about 20-fold from 1960 to 2010 in China. Despite this remarkable growth, the average OECD citizen was still about 10 times richer than the average Chinese citizen in 2010. The BaU scenario displays a progressive convergence of income per capita but the gap still remains wide for many decades: in 2050 GDP per capita is about three times higher in OECD economies than in China, in 2100 about two times higher.

The persistence of the income gap between the richest economies and China has – and will have – important repercussions in all international negotiations to share the global cost of containing global warming. However, China will surpass the world average per capita GDP between 2030 and 2050, in our scenarios. Thus, China will emerge as a peculiar actor in future climate negotiations. From one side, there are factors that will push towards a limited involvement: China will not be as affluent as the major world economies for most of the century and Chinese emissions per capita will still be 50 per cent lower than in OECD economies. On the other side, there are factors that will push towards a higher commitment: China is and will likely remain the major emitter of GHG during the whole century – capable of nullifying the efforts of other economies to control global warming – with a growing responsibility towards all poorer economies that will bear heavy negative climate change impacts (Blanford *et al.*, 2008; Carraro and Massetti, 2011; Massetti, 2011; Zhang, 2011).

The rise of energy consumption during the past 30 years has been much less impressive than the rise of the economy in China (see table 1 and figure 1), making it possible to produce in 2005 the same level of aggregate output as in 1975 with only one-fourth of energy inputs (see figure 2).

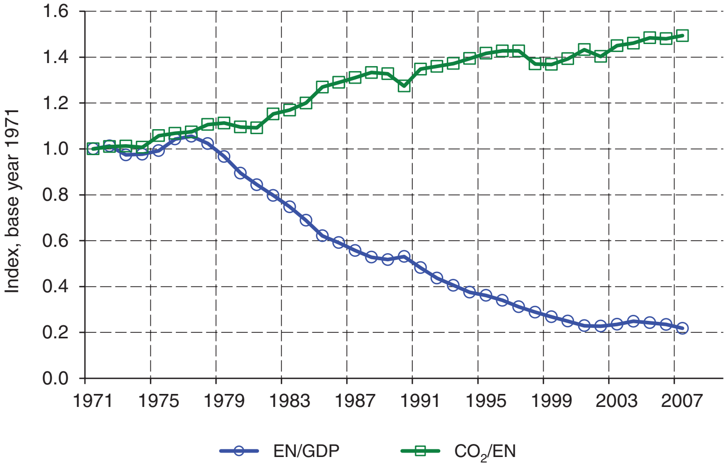

Figure 2. *The indices of energy intensity of GDP and of carbon intensity of energy*
Source: See notes to table 1. Base year 1971.

Levine *et al*. (2009) distinguish among three different eras in China's energy story. The first is the 'Soviet Model' and goes from 1949 to 1980. In these early years of the communist regime, China followed the Russian model with low energy prices, predominance of heavy industries and no concern for environmental effects. This led to very high inefficiencies both on the demand and the supply side. The 'Classic' period goes from 1980 through 2002. In 1980 Deng Xiaoping stated as a goal to quadruple GDP while only doubling energy consumption between 1980 and 2000. New institutions were created to promote energy conservation, the most important among them being the Bureau of Energy-Saving and Comprehensive Energy Utilization in the State Planning Commission. Energy conservation centres were spread throughout the country, employing more than 7,000 people at their peak. All these efforts – together with a long-term shift of the economy towards less energy-intensive industries – explain the success of Chinese energy demand management, well beyond Deng Xiaoping's expectations. Finally, from 2002 through 2005, China lived through a third phase, that of 'Out-of-control Growth' in energy demand (see figures 1 and 2). Levine *et al*. (2009) believe that the sharp increase in energy use and the reversal of the long-term energy intensity trend is explained by more lenient policies to manage energy demand and by a fast expansion of energy-intensive industries, stimulated by exports (China entered the WTO in 1995) and by domestic demand (cement and steel to build infrastructures). Emissions of CO_2 skyrocketed from 2002 to 2005, surpassing US emissions in 2006 (Levine and Aden, 2008), between nine and 14 years earlier than what was estimated in 2004.

The share of fossil fuels in total energy consumption has increased during the past 30 years. Fossil fuels covered 64 per cent of energy demand in 1975, 75 per cent in 1990 and about 80 per cent in 2010 (table 1). Coal – the fossil fuel with the highest content of carbon per unit of energy – has played a major role in satisfying the growing appetite for energy in China. Between 2003 and 2005 the power sector saw the fastest expansion ever recorded in world history: 66 GW of new capacity were installed each year, with a dominant role for coal-fired power plants (Zhou *et al.*, 2010). About 200 GW of new capacity translates into more than one large coal power plant of 1 GW per week. Since the expected lifetime of coal-fired power plants is about 40 years, three years of 'Out-of-Control Growth' of energy will have repercussions on global CO_2 emissions for many decades.

Energy use increases 260 per cent between 2010 and 2050 in our BaU scenario. After 2050 energy demand reaches a plateau. For a comparison, energy demand from OECD economies increases by only 12 per cent from 2020 to 2050 and remains flat for the next 50 years. At the global level an extra 9,000 Mtoe (million tonnes of oil equivalent) of energy will be needed in 2050 with respect to 2010; 35 per cent of this incremental demand will go to China. The rest of the developing countries will instead generate the largest fraction of energy demand after 2050. The growth of energy demand is mitigated by strong efficiency gains: in 1990 China used 1.9 tonnes of oil equivalent (toe) per US$1,000 of output, in 2050 0.16 toe. China reduces its energy intensity of output twice as fast as the OECD economies between 2010 and 2050 (table 1). The average annual optimal contraction of energy intensity in our BaU scenario is equal to 3.0 per cent from 2010 to 2050, a slower improvement than that witnessed during the past 20–30 years but a net reversal compared to the 'Out-of-Control' years in which energy intensity increased by an average 3.8 per cent per year.

There are reasons to expect that a fourth era in the Chinese story of energy efficiency is about to begin. Levine *et al.* (2009) call this a 'modern re-enactment of the early days'. A key role will be played by governmental regulation. In November 2005 the Politburo mandated a 20 per cent reduction by 2010 in energy intensity, compared to 2005 (an average 4.3 per cent per year). It is early to assess if the Chinese government achieved this target, but preliminary data show that energy intensity declined by 19.1 per cent between 2006 and 2010 (Zhou *et al.*, 2011).

Chinese officials perceive all the threats that an out-of-control expansion of energy demand will pose to future economic growth and have put energy efficiency again at the top of their agenda. 'Ten Key Projects' were incorporated in the 11th Five Year Plan. The most important actions include: the renovation of coal-fired industrial boilers; district-level combined heat and power projects; oil conservation and substitution; and energy efficiency and conservation in buildings (Levine *et al.*, 2009; Zhou *et al.*, 2010). A decisive contribution to higher energy efficiency will come from market forces: energy prices are currently reflecting their actual cost in China (IEA, 2007); electricity prices were increased from 0.43 RMB/kWh in May 2004 to 0.51 RMB/kWh in July 2006 (Moskovitz *et al.*, 2007).[4]

An intense debate on the future pattern of energy efficiency in China occurred after China pledged in the Copenhagen Accord to reduce the

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[4] IEA (2007) and Moskovitz *et al.* (2007), cited in Zhou *et al.* (2010).

GHG emissions content of GDP by 40–45 per cent in 2020 compared to 2005. Although not binding, this target reflects the present commitment of Chinese authorities to reduce GHG emissions.[5] We cannot address this issue with sufficient precision because our scenarios reflect long-term growth and energy sector dynamics rather than short-term fluctuations of the economic cycle. However, our scenarios indicate that the Copenhagen pledge could be achieved in a BaU scenario. This does not mean that the target will not present challenges. It rather indicates that it is in the self-interest of China to increase energy efficiency, without accounting for the global environmental benefits.

With respect to other scenarios in the literature, our BaU has an optimistic view of the energy efficiency potential in China in the next decades (ERI, 2009; IEA, 2010; Zhou *et al*., 2011). On the other hand, we have a pessimistic outlook in terms of carbon content of energy and see a prolonged use of coal in the power sector. Although renewables and nuclear are by far the energy sources with the fastest growth rate in our BaU scenario, they remain marginal for many decades (see tables A2– A5 in the online appendix available at http://journals.cambridge.org/EDE). In our BaU scenario the share of fossil fuels in energy use increases from 85 to 92 per cent in 2050, in line with the historic trend (figures 1 and 2); the carbon content of energy remains roughly the same during the whole century. Total emissions are therefore driven by population, economic growth and energy use.

A moderate growth of population, a fast expansion of economic activity and a marginal increase in carbon intensity of energy translate into a 260 per cent expansion of CO_2 emissions from fuels use from 2010 to 2050, and an additional 17 per cent increase from 2050 to 2100. In 2050 China emits as much CO_2 from fuel combustion as the whole OECD. However, emissions per capita remain lower than in OECD economies. They are instead much higher than in the rest of the world. Contrary to the 2050 outlook of Zhou *et al*. (2011), we do not see emissions peaking, not in 2030, nor in any other period. We have a trajectory that is closer to Blanford *et al*. (2008), ERI (2009) and IEA (2010).

One explanation behind the continuous growth of emissions in our BaU scenario is certainly the absence of any policy that constrains the use of fossil fuels, for local or global concerns. Another possibility is that we underestimate the long-term penetration potential of nuclear and natural gas, especially if low-cost shale gas becomes available. While we leave for future research the analysis of alternative BaU scenarios, in the next section we study how the Chinese economy reacts to five different carbon tax scenarios in our model. Scenarios in which energy use is constrained for domestic reasons are also left for future research.

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[5] China also committed to increase the share of non-fossil fuels in primary energy consumption to around 15 per cent by 2020 and to increase forest coverage by 40 million ha and forest stock volume by 1.3 billion m^3 by 2020 from the 2005 levels.

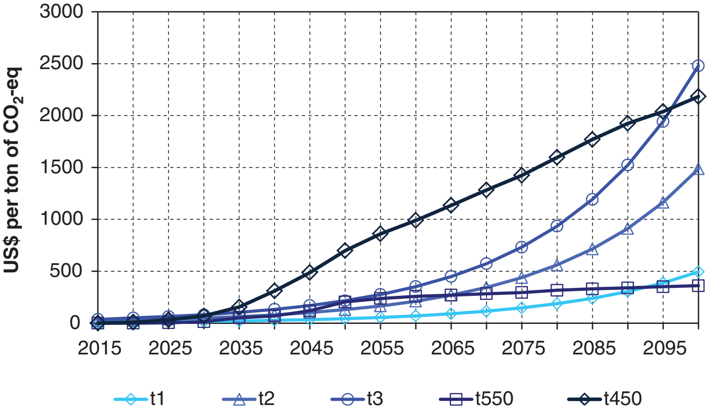

Figure 3. *The tax scenarios*
Note: All GHG emissions included.

3. Climate policy scenarios

In this section we explore scenarios in which explicit policy measures are taken to reduce the level of GHG emissions in China. We focus on five emission tax scenarios which span a wide range of emission reduction targets.[6] For the first three scenarios (t1, t2, t3), the tax rate starts at US$7, US$21 and US$36 per ton of CO_2-eq (/tCO_2e) in 2015. In all three scenarios the tax then increases at 5 per cent per year. The other two scenarios (t550, t450) are designed to stabilize radiative forcing at 3.8 and 2.7 w/m^2, roughly 550 and 450 ppme.[7] Carbon pricing starts in 2025 (t550) and 2020 (t450). The t450 scenario keeps temperature increase above the pre-industrial level of below 2°C during the whole century. We assume that the same tax applies to all world regions. Therefore we include spillovers on natural resources use and on technological progress triggered by climate policy. Figure 3 displays the time path of the carbon taxes.

Figure 4 displays the pattern of emissions in the BaU and in the policy scenarios in China and in the OECD. The t450 scenario is the most demanding in terms of emission reductions, followed closely by the t3 and the t2 scenarios. The t550 scenario is less demanding than the t3 and t2 scenarios in the first and last decades of the century. The t1 scenario can be considered a 550 ppme with 'overshoot' scenario: emissions eventually reach the t550 level, but are much higher during the transition.[8] While emissions

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[6] For simplicity, we often refer to the tax on all GHG emissions as 'carbon tax'.

[7] The emissions tax is obtained by solving the model imposing a global pattern of emissions that is consistent with the 2100 radiative forcing target and allowing countries to trade emissions allowances internationally to equate marginal abatement costs. We then run the model imposing the carbon price as a tax, thus avoiding complex distribution issues.

[8] WITCH is a perfect foresight model. The level of future taxation influences present decisions. Therefore it is optimal to smooth the transition to a regime of emissions

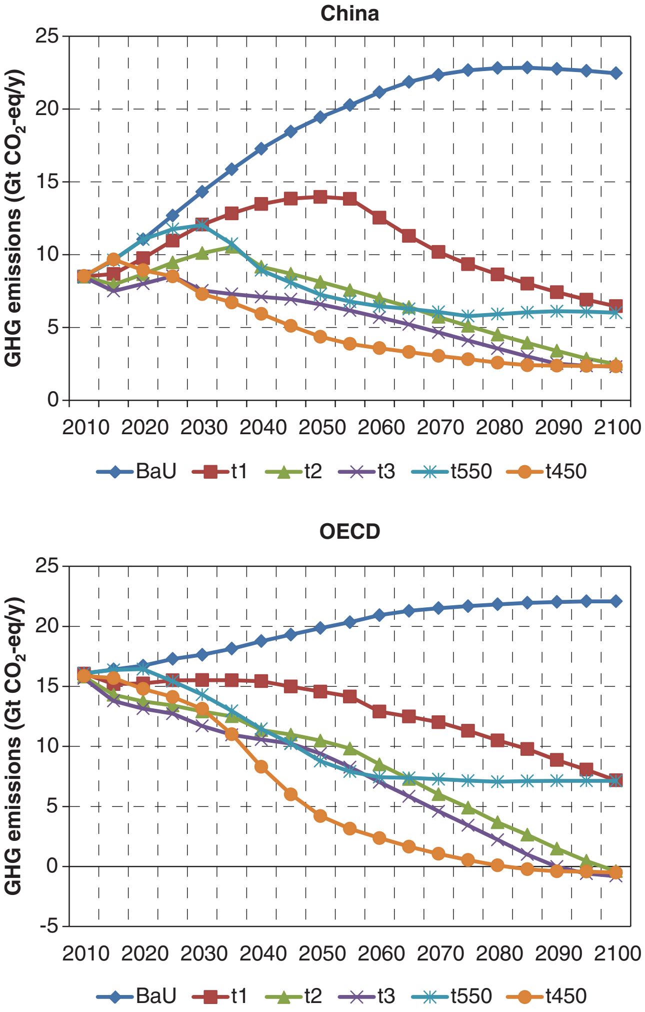

Figure 4. *The time pattern of GHG emissions in China and in OECD economies, in the BaU and in the tax scenarios*

start declining immediately in OECD economies, in China only with the very aggressive t3 and t450 taxes do emissions peak before 2025. The other remarkable difference with respect to OECD economies is that emissions never become negative. This happens because OECD economies have relatively more abundant biomass and lower residual emissions than in China. Therefore BECCS – which generates electricity while absorbing emissions from the atmosphere – generates net negative emissions.

taxes in WITCH. This explains why emissions decline with respect to the BaU before 2020 in figures 4 and 5.

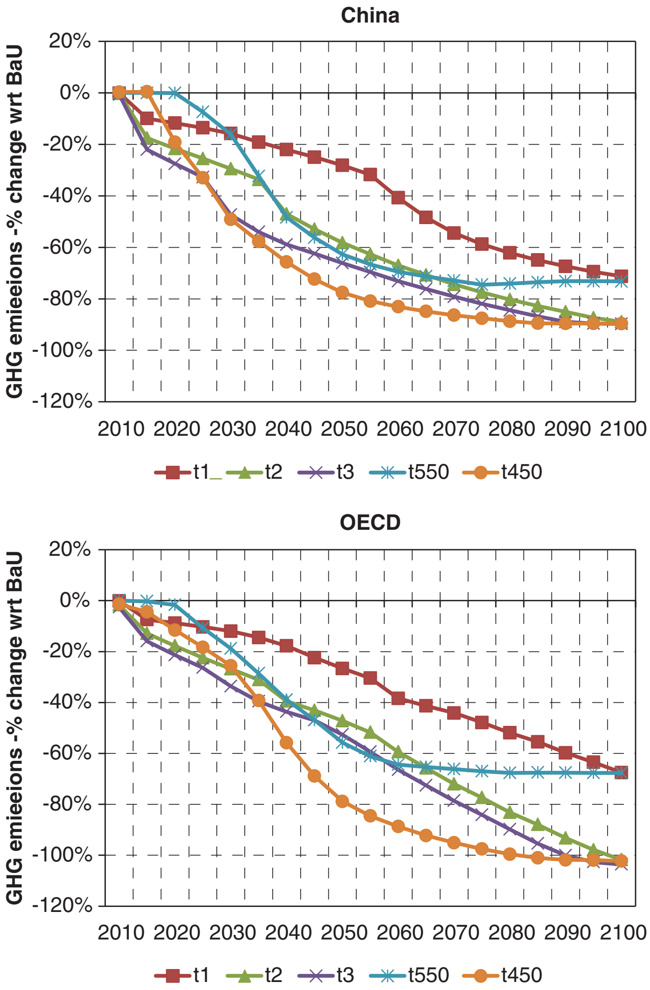

Figure 5. *Change of GHG emissions trajectories with respect to the BaU in China and in OECD economies*

Figure 5 displays the percentage deviation of emissions in each tax scenario with respect to the BaU. The Chinese economy initially is relatively more elastic than the OECD, because lower energy efficiency and higher carbon intensity offer relatively cheaper abatement options. In 2050, the response of the two economies is instead very similar. This intuition is confirmed by the analysis of the relationship between carbon taxes and emission reductions.

If we pool all our climate policy scenarios, we have about 100 different combinations of carbon taxes and GHG emission levels. We use this rich set of model-generated observations to estimate a more general relationship between carbon taxes and the optimal abatement level in both China and

OECD economies (figure 6A). The elasticity of emission reductions with respect to the BaU is not constant for both China and the OECD. For a low level of taxation, China is more elastic than the OECD: at US$25 the elasticity is 0.60 for China and 0.55 for the OECD. They have the same elasticity at US$51 and then China becomes less elastic: at US$500 the elasticity is 0.19 for China and 0.33 for the OECD.[9] From another perspective, figure 6A reveals that China has a flatter marginal abatement cost curve for low levels of the tax than the OECD and a steeper curve for high tax levels.

If we consider abatement with respect to the BaU, figure 6A reveals that China and the OECD behave quite similarly when subject to a carbon tax. Instead, if we consider the rate at which emissions are reduced with respect to the year 2010, we find a totally different pattern, as shown in figure 6B. When the tax is roughly lower than US$125, emissions still increase with respect to the base year in China, while they decline for any level of taxation in the OECD. The major reason is that China's economy grows faster than the OECD economies for many decades in our scenarios, providing continuous pressure on energy demand and emissions.

A useful exercise is to assess the level of the tax that is coherent with the long-term mitigation targets set during the Major Economies Forum (MEF) meeting at the 2009 G8 Summit in Italy. MEF leaders announced that they intend to cut global emissions by 50 per cent in 2050 with respect to 2005. High income economies will take the lead and cut their emissions by 80 per cent. This implies that developing countries must reduce their emissions by about 30–35 per cent with respect to 2005, according to our BaU scenario. Figure 6B gives a measure of how expensive this target can be for developing countries in general and China in particular: the tax should be between US$250 and US$500 to achieve the desired emission reductions. Furthermore, it is realistic to assume that China would be required to reduce emissions more than the least developed countries. A 50 per cent contraction with respect to 2005 seems a reasonable guess for China. In that case, the tax should rise up to about US$750, in the same range as the tax level necessary to reduce emissions by 80 per cent with respect to 2005 in the OECD. Therefore, the MEF target seems ambitious. It asks for a very high level of taxes, and the distribution of effort among world countries does not stand a preliminary fairness test.

A caveat applies to our analysis: by pooling all observations we implicitly assume that the elasticity of emissions to carbon taxes is time independent. This is obviously not true. Technical progress, economic growth, price changes in non-renewable sources of energy, and many other important drivers change over time and affect marginal abatement costs. A tax of US$1,000 would definitely trigger a very different reaction if applied in 2010 rather than in the second half of the century. However, if we assume

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[9] Denoting with y the reduction of emissions with respect to the BaU and with x the tax level, we estimate the following functional form using OLS: $\ln(y_i) = \alpha_i + \beta_i \ln(x_i) + \gamma_i[\ln(x_i)]^2 + \varepsilon_i$. The number of observations is 84. The coefficients are all significant at the 1 per cent level: $\alpha_{\text{china}} = -4.05$; $\beta_{\text{china}} = 1.03$; $\gamma_{\text{china}} = -0.07$. $\alpha_{\text{oecd}} = -3.81$; $\beta_{\text{oecd}} = 0.79$; $\gamma_{\text{oecd}} = -0.04$. The adjusted R^2 is equal to 0.968 for China and 0.963 for the OECD.

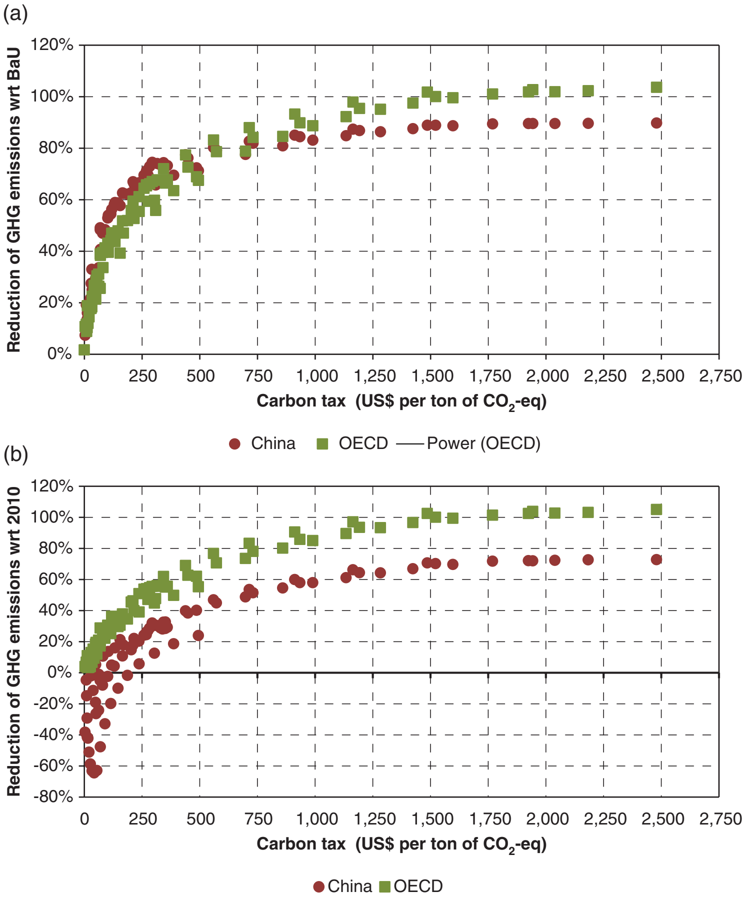

Figure 6. *The impact of the carbon tax on GHG emissions*
Note: Panel A: abatement expressed in percentage of all GHG emissions with respect to the BaU. Panel B: abatement expressed in percentage of all GHG emissions with respect to 2010. All data points from the five tax scenarios are pooled together.

that the optimal pattern of taxes increases gradually over time and rule out extreme possibilities, we find that the loss of precision is small (see table A1 in the online appendix).[10] We believe that the insights that we obtain using an observations-based analysis rather than a scenario-based

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[10] For example a tax of US$100 in 2035, 2045 and 2070 would induce a −54 per cent, −53 per cent, −54 per cent change of emissions respectively with respect to the BaU in China and a −40 per cent, −43 per cent, −44 per cent change in the OECD. A tax of US$50 in 2030, 2035, 2050, would induce a −29 per cent, −32 per cent, −32 per cent change of emissions respectively in China and a −27 per cent, −29 per cent, −30 per cent in the OECD.

analysis are greater than the loss of precision which we incur by treating marginal abatement costs as time independent.

The transformations induced by climate policy can be grouped into two major categories: those increasing energy efficiency and those decreasing the carbon content of energy. Figure 7 gives a synthetic description of optimal movements along the dimension of energy efficiency and of de-carbonization of energy. In both China and the OECD energy efficiency increases substantially in the BaU. While carbon intensity of energy remains rather stable in China, in our BaU scenario it is optimal to increase the carbon intensity in OECD economies: without any concern for global warming world countries continue to rely for many decades on abundant and relatively cheap fossil fuels.

The introduction of emission taxes reinforces the trend of energy efficiency improvements and tilts all curves downward, indicating a substantial de-carbonization of energy in all scenarios. Energy efficiency improves much faster in China than in the OECD. The de-carbonization of the economy proceeds instead at a very similar pace, as highlighted by the solid dark line that marks 2050. However, China reaches a lower bound to the carbon intensity of the economy in 2100.

What are the transformations needed in the power sector to substantially reduce the carbon content of energy in China? High carbon taxes drastically reduce the attractiveness of cheap fossil fuels in power generation. For example, the tax on each kWh generated with traditional coal power plants in China would range between 0.3 and 6.0 cents in 2030, between 2.8 and 40 cents in 2050, and between 27 cents and US$1.55 in 2100. During the same time the cost of the power plant would decline from about 2 cents per kWh to about 1 cent. Therefore the carbon tax component would dwarf any other investment, maintenance and operation cost. To a lesser extent, the same applies to natural gas without CCS.

We again pool all observations that we obtain from our five carbon tax scenarios and we derive a relationship between the level of the carbon tax and the share of total electricity generation covered by a given technology. Tables A2 and A3 in the online appendix provide data on electricity generation by scenario, year and technology.

Figure 8 focuses on fossil fuel-based technologies. Coal without CCS rapidly declines, faster in China than in the OECD: the elasticity is equal to −0.89 in China and −0.80 in the OECD. However, with a tax roughly equal to US$250, China still covers between 5 and 15 per cent of electricity with coal, while in the OECD the share is not higher than 3 per cent. Coal with CCS expands rapidly but also rapidly reaches a peak: around US$270/t$CO_2$e in China and US$130/tCO_2e in the OECD. At the peak, coal with CCS covers about 25 per cent of total electricity production in China, but only about 10 per cent in the OECD. Coal with CCS is a bridge technology, much more important in China than in the OECD. Gas power generation plays a minor role in China, but when a tax on emissions is introduced it offers a first alternative to carbon-intensive coal. The share of gas increases from 2 to 5 per cent when the tax reaches about US$100 t/$CO_2$e, then it rapidly declines. In OECD countries the share of gas is initially much larger than in China, but it quickly converges to the

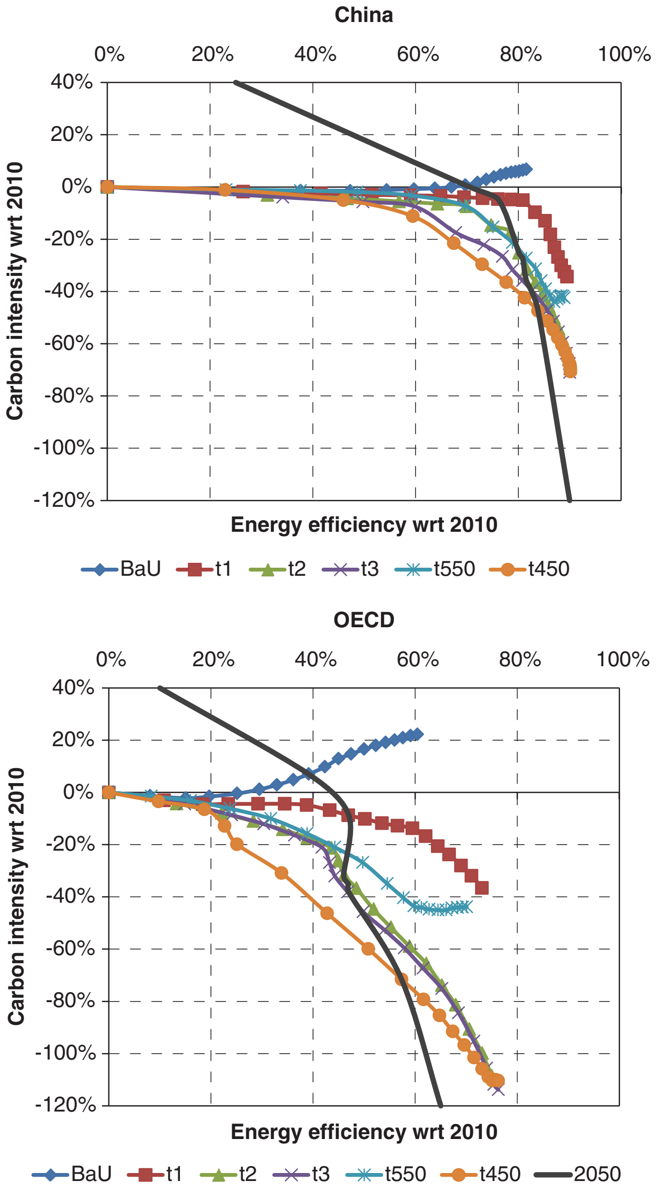


Figure 7. *The time pattern of the carbon intensity of energy and the energy efficiency of the economy in China and in OECD countries*
Note: Each data point marks the combination of carbon intensity and energy efficiency with respect to 2010, in percentage. We consider only CO_2 emissions from fossil fuels. Each marker corresponds to a year, from 2010 to 2100. The solid black line marks the year 2050.

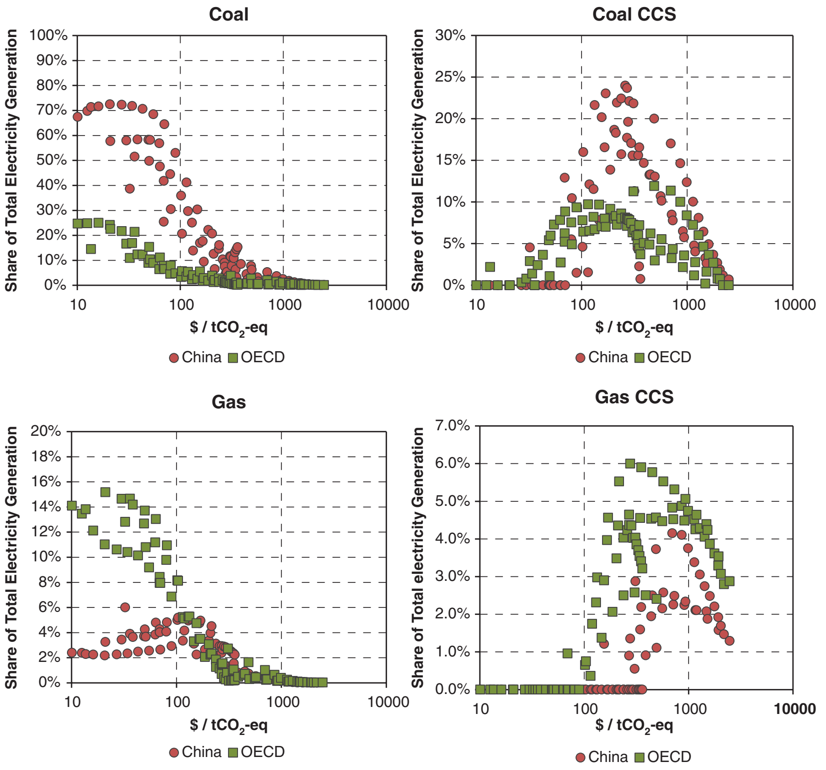


Figure 8. *Carbon taxes and technological dynamics: fossil fuels and low/zero-carbon substitutes*
Note: The horizontal axis has logarithmic scale.

same level as China when the tax reaches US\$100 t/CO_2e. For higher levels of the tax gas is gradually phased out in both China and the OECD. Gas with CCS starts to emerge as a viable option at about US\$100 t/CO_2e; however, it covers at most 6 per cent of total electricity supply in the OECD and only 4 per cent in China. It peaks at about US\$275 in the OECD and US\$700 in China.

Figure 9 focuses on zero or negative emissions technologies. Nuclear power is an ideal candidate to substitute coal power plants in China and increases steadily up to 60 per cent of total electricity generation. In the OECD nuclear already covers about 30 per cent of TPES in 2010 and would slightly increase up to 40 per cent in the BaU scenario. The carbon tax increases its penetration with respect to the BaU, but only marginally. The figure portrays a striking contrast between the future for nuclear in China and the OECD. It is important to note that limits to the deployment of nuclear for security concerns would alter greatly this picture. Wind power becomes an important component of electricity supply when the tax increases above US\$100 t/CO_2e in China; in the OECD wind is adopted already at relatively low carbon prices. While the investment cost declines

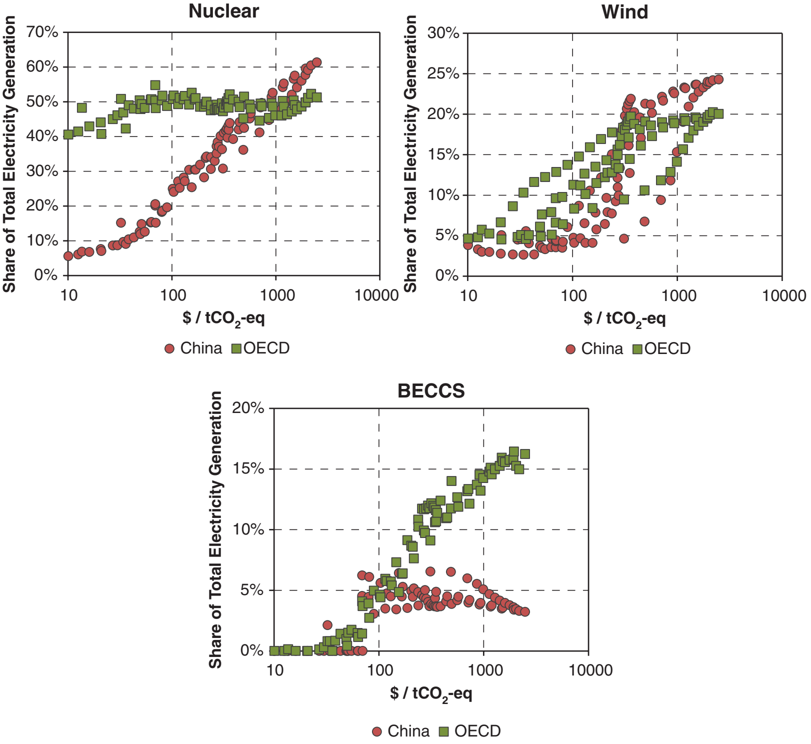
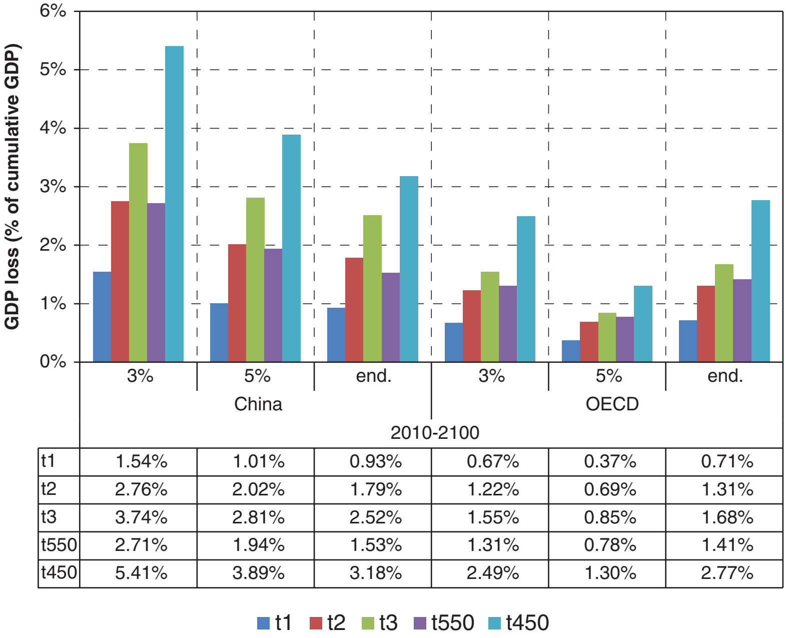


Figure 9. *Carbon taxes and technological dynamics: carbon-free technologies*
Note: The horizontal axis has logarithmic scale.

as global cumulative installed capacity increases, the exhaustion of the best sites and grid management penalty costs constrain the expansion of wind in both China and the OECD. We find that wind has an extra 5 per cent penetration potential in China with respect to OECD economies. Finally, BECCS has the advantage of being a net sink for emissions. OECD economies have much a larger supply of biomass than China in our scenarios and can use it in combination with coal in IGCC power plants to supply up to 15 per cent of electricity generation with the highest tax levels. BECCS becomes a valid alternative when the tax reaches US\$100 t/CO_2e in China; it reaches the maximum generation potential and remains stable thereafter. In the OECD, BECCS becomes part of the generation portfolio, with taxes just above US\$50 t/CO_2e. The limits to the expansion of BECCS greatly influence the cost to comply with the highest tax levels. Further analysis is necessary to introduce international trade of biomass and alternative assumptions on biomass potential. Photovoltaic is considered part of a general carbon-free backstop technology in the newest version of WITCH. The initial cost is too high compared to other alternatives, but investments in R&D can make it competitive. We do not find any incentive to invest in new carbon-free power generation technologies because we let nuclear and



	China 3%	China 5%	China end.	OECD 3%	OECD 5%	OECD end.
t1	1.54%	1.01%	0.93%	0.67%	0.37%	0.71%
t2	2.76%	2.02%	1.79%	1.22%	0.69%	1.31%
t3	3.74%	2.81%	2.52%	1.55%	0.85%	1.68%
t550	2.71%	1.94%	1.53%	1.31%	0.78%	1.41%
t450	5.41%	3.89%	3.18%	2.49%	1.30%	2.77%

Figure 10. *The cost of reducing GHG emissions*

Note: Costs are expressed as the ratio between the discounted sum of GDP losses with respect to the BaU scenario and cumulative discounted GDP in the BaU scenario. Interest rate: 3%, 5% and the endogenous region-specific interest rate of the model. The interest rate for OECD economies is an average of five regions' interest rates, with weights equal to their GDP. In the BaU, the interest rate is equal to 12% in China and to 3.6% in the OECD, in 2010; in 2100 the interest rate is equal to 1.5% in China and 1.6% in the OECD. The interest rate used varies among tax scenarios.

CCS expand without any constraint. Opposition to nuclear and opposition to or technical problems in CCS would push investments in the backstop power generation technology (see for example Bosetti *et al.*, 2009a).

Macroeconomic discounted costs of emission reductions are displayed in figure 10. Costs are measured as the ratio between discounted GDP losses and BaU discounted GDP. We use three different discount rates: 3 per cent constant, 5 per cent constant, and the endogenous rate of return on capital investments, which is equal to the marginal product of capital. Rates of returns are not equalized because we do not assume capital mobility. This is of course a rough representation of world capital markets, but it has the advantage of generating higher rates of return in developing countries than in developed economies without the complexities of imperfect capital mobility models. Rates of return decline endogenously as capital accumulation proceeds. The pure time preference rate is instead the same in all countries, equal to three at the beginning of the century and declining over time.

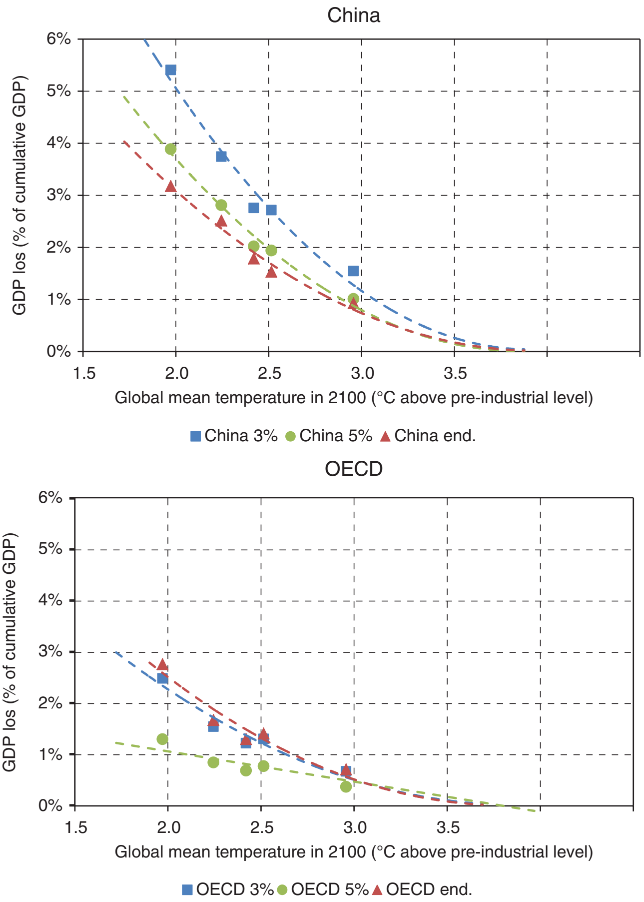


Figure 11. *Marginal temperature control cost curves*
Note: Fitted curves are dashed. We estimate a quadratic relationship except for the OECD when the interest rate is equal to 5%. For China the coefficients have all p-values lower than 0.05. The adjusted R^2 are as follows: 0.987 (5%), 0.981 (3%), 0.982 (end.). For the OECD, the coefficient of the temperature squared has a p-value equal to 0.147 in the 5% case, thus we adopt a linear relationship. The adjusted R^2 is equal to 0.873; in the 3% case the p-value of temperature squared is equal to 0.07, the adjusted R^2 is equal to 0.935; when we use the endogenous interest rate the p-values are below 0.05, the adjusted R^2 is equal to 0.948.

Costs are much higher in China than in OECD economies if the 3 per cent or the 5 per cent interest rates are used. With the endogenous interest rate (our preferred choice), the cost of climate policy is always higher in China, but the gap with the OECD diminishes. China abates relatively more than the OECD for a tax level below US$500 (see figure 6). This is typically a price range that we find in early years, when the interest rate in China is high, which contributes to the sharp reduction of costs if measured using the endogenous interest rate. The OECD contributes instead relatively more when the tax is very high. Since this typically happens in late years, with a 5 per cent constant interest rate the cost of climate policy appears very low in the OECD. If we use instead the endogenous interest rate the cost doubles.

Figure 10 has important implications for future negotiations on climate change as countries will not accept excessively high policy costs. Bosetti and Frankel (2012) have examined an international climate architecture which is based on the postulate that countries will not cooperate to reduce emissions if – among other conditions – costs exceed 1 per cent of GDP in discounted terms. If we use endogenous interest rates, this limits politically feasible action to the t1 scenario, which delivers a temperature increase far above the 2°C. If the bar is raised to 1.5 per cent, the 550 ppme stabilization target becomes feasible and the cost would be roughly the same in the OECD and in China.

It must be recalled, however, that we are not counting the benefits from reduced warming. If climate impacts will be felt more at the end of the century, lower/higher interest rates would discount more/less the future benefits of climate policy, balancing (at least in part) the effect of interest rates on discounted costs. A careful evaluation of the incentives to participate in a global deal on climate change requires a cost-benefit analysis in a coalition theory framework, which is beyond the scope of this work.

Finally, it is instructive to relate the temperature level in 2100 to the cost of achieving that level. Figure 11 reproduces marginal temperature control cost curves obtained by pooling all scenarios for China and the OECD, using different interest rates. When we use endogenous interest rates, we find a quadratic relationship between the temperature level and the cost. When we use constant 3 per cent or 5 per cent interest rates, the curve becomes steeper in China and flatter in the OECD. With high discount rates the curve becomes linear in the OECD. The choice of the appropriate interest rate is therefore crucial and has very different implications in countries at different levels of economic development.

4. Conclusions

This paper uses historic data and scenarios on future economic development, energy use and emissions developed using the WITCH model to convey six key messages.

First, without specific climate policy measures, China's emissions are likely to grow substantially in the next decades. Even if energy efficiency improvements return to the fast pace that was recorded in the 1980s and 1990s, continued economic growth and a rather stable carbon content of energy would not stabilize GHG emissions.

Second, despite fast economic growth, in our BaU scenario China will have a relatively low level of GDP per capita for many years still. The gap between China and the OECD economies, in terms of GDP per capita, will narrow but will remain substantial. China will therefore be in the peculiar position of being the greatest emitter of GHG but at the same time not rich enough to afford costly abatement measures.

Third, by pooling all the tax emission reductions combinations from the five tax scenarios, we find that the elasticity of emissions is higher in China than in the OECD until the tax reaches US\$500/tCO_2-eq. This implies that China will abate emissions more than the OECD when the tax is low. For high levels of the tax, emissions become very inelastic in China.

Fourth, attaining the 2009 Major Economies Forum goal of reducing global emissions by 50 per cent can be very expensive for China and other developing countries. Our best guess indicates that China would need to introduce a tax equal to about US\$750/tCO_2-eq in 2050 to achieve that goal. This is in line with what is required in OECD economies, which are more flexible and can reduce emissions by 80 per cent below present levels, as promised by the MEF. This target is only aspirational and far from being part of an international treaty. However, it offers a useful benchmark to evaluate possible future climate policy scenarios.

Fifth, in our preferred estimates, the discounted cost of following the 2°C trajectory is equal to 5.4 per cent and to 2.7 per cent of GDP, in China and the OECD, respectively. All other policy targets are more expensive for China than for the OECD. This calls for a more equitable distribution of the mitigation burden among world countries. If this is believed to be inefficient, very high compensations are necessary to steer China towards a 2°C compatible trajectory.

Finally, a mild commitment to introduce some sort of emissions pricing in China is much needed in a post-2020 climate architecture. Even a modest contribution would be extremely important due to the scale of emissions from China. The lowest tax scenario that we study (US\$10/tCO_2e in 2020, US\$43 in 2050, US\$495 in 2100) could be a useful starting point in the next round of negotiations. It could be politically feasible and at the same time bring large emission reductions in China.

Because of the crucial role that China has and will have in determining the global future climate, it is of utmost importance that the gap between the stated goals and what appears politically feasible is filled in the next 10–20 years.

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