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Implications of the international reduction pledges on long-term energy system changes and costs in China and India

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HIGHLIGHTS

- We analyze long-term impacts of the international pledges for China and India.
- We compare a least-cost pathway with a pathway starting from the Copenhagen pledges.
- Postponing mitigation action implies much higher cumulative mitigation costs.
- Postponing increases fossil fuel dependence and requires deeper long-term reductions.
- Countries differ mainly due to different periods of rapid economic change.

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ABSTRACT

This paper analyses the impact of postponing global mitigation action on abatement costs and energy systems changes in China and India. It compares energy-system changes and mitigation costs from a global and two national energy-system models under two global emission pathways with medium likelihood of meeting the 2 °C target: a least-cost pathway and a pathway that postpones ambitious mitigation action, starting from the Copenhagen Accord pledges. Both pathways have similar 2010–2050 cumulative greenhouse gas emissions. The analysis shows that postponing mitigation action increases the lock-in in less energy efficient technologies and results in much higher cumulative mitigation costs. The models agree that carbon capture and storage (CCS) and nuclear energy are important mitigation technologies, while the shares of biofuels and other renewables vary largely over the models. Differences between India and China with respect to the timing of emission reductions and the choice of mitigation measures relate to differences in projections of rapid economic change, capital stock turnover and technological development. Furthermore, depending on the way it is implemented, climate policy could increase indoor air pollution, but it is likely to provide synergies for energy security. These relations should be taken into account when designing national climate policies.

1. Introduction

Limiting global mean temperature increase to 2 °C compared to pre-industrial levels will require a major reduction of greenhouse gas (GHG) emissions in the coming decades (IPCC, 2007; Van Vuuren et al., 2011). In the last decade, already in absolute terms, most emission growth originated from developing countries, in particular from the so-called emerging economies such as China and India. In fact, China and India are already the largest and third largest global emitting country of CO_2 emissions, respectively (Olivier et al., 2012). Their large and increasing population and fast economic development are expected to drive their CO_2 emissions even further. Model projections show the contribution of China and India to global total energy-related CO_2 emissions to increase from 30% in 2010 to around 40% in 2050 (OECD, 2012). Without major emission reduction efforts and early participation of both China and

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India, before 2025, the 2 °C target cannot be reached (Metz et al., 2002; Höhne et al., 2006; Van Ruijven et al., 2012b).

After the UN climate negotiations held in Copenhagen in 2009, many industrialized and developing countries have submitted reduction proposals (pledges) and mitigation actions to the UNFCCC secretariat, which have been included in the Appendices of the Copenhagen Accord (UNFCCC, 2009), and later 'anchored' in the 2010 Cancún Agreements (UNFCCC, 2010a, 2010b). Also China and India made pledges. China pledged to improve their CO_2 emissions per unit of GDP in 2020 by 40% to 45% relative to 2005 levels, while India pledged to improve their GHG emissions (excluding agriculture) per unit of GDP in 2020 by 20% to 25% relative to 2005 levels. Although the aggregated pledges of all countries are likely to reduce GHG emissions below business-as-usual levels, their combined impact seems not adequate to reach a level consistent with a least-cost pathways that achieves the 2 °C target (UNEP, 2012).

The timing of emission reductions has been subject to debate for a long time (Wigley et al., 1996; Azar, 1998; Clarke et al., 2009). In the context of the 2020 pledges, decisions should be based on an evaluation of short-term limitations in emission reductions, long-term expectation on technology development, stimulation of learning, costs and risks of temperature overshoot (Den Elzen et al., 2010; Van Vuuren and Riahi, 2011; OECD, 2012; Van Vliet et al., 2012).

Many studies discuss emission reduction trajectories in China and India that are compatible with the 2 °C target as well as the required changes in their respective energy systems (Shukla and Dhar, 2011; Steckel et al., 2011; Calvin et al., 2012; Kejun et al., 2012; Shukla and Chaturvedi, 2012; Van Ruijven et al., 2012a). Most of these studies, however, do not take the specific 2020 country pledges into account. This paper, instead, explores the energy-system and mitigation cost implications for China and India of globally postponing emission reduction effort, by comparing a least-cost pathway (early action) with a pathway which assumes that in 2020 first the country pledges are implemented after which a 2 °C emission pathway is followed (delayed response). The paper also analyses the differences in response strategies between China and India and the interrelations of climate policy with national issues, i.e. energy access and energy security. The analysis is based on the results from a multi-model comparison study (see Johansson et al., submitted for publication) using a global climate policy model, a global energy-system model and two national energy system models for China and India.

Section 2 presents the modelling framework and describes the different models that are used. Section 3 introduces the reference scenario and the two global emission pathways that are used in our analysis. Section 4 presents results for CO_2 emissions, energy system changes, and climate policy costs and Section 5 discusses trade-offs and co-benefits of climate policies. Finally, Section 6 discusses the methodology and findings and draws some general conclusions.

2. Modelling framework

The analysis uses a set of soft-linked models, including a global climate policy model and three energy-system models. The models are soft-linked in the sense that the output from one model (here FAIR) is used as input to other models (here the energy-system models). The global climate policy model FAIR (Den Elzen and Lucas, 2005; Den Elzen et al., 2008) is used to construct the CO_2-equivalent emission pathways[1] compatible with a ~50% chance of staying within 2 °C temperature increase in 2100, and associated carbon taxes. Fair also determines total climate policy costs. The associated carbon taxes from FAIR are input for three energy systems models that are used to determine changes in energy production and consumption, and to calculate total climate policy costs (MARKAL models only). TIMER[2] is a recursive dynamic global energy-system model that describes the long-term dynamics of the production and consumption of energy for 26 world regions, including China and India (Van Vuuren et al., 2006; 2007). China MARKAL (Chen, 2005; Chen et al., 2007; Chen et al., 2010) and ANSWER MARKAL (Shukla, 1997; Shukla et al., 2008) are national energy system optimization models for China and India, respectively. Both are based on the MARKAL modelling system (Fishbone and Abilock, 1981). In the rest of this paper we will refer to MARKAL China for the Chinese version and MARKAL India for the Indian version.

The **FAIR** model links long-term climate targets and global reduction objectives with regional emissions allowances and abatement costs. The model includes the models FAIR–SiMCaP (Den Elzen et al., 2007) and the MAGICC 6 climate model (Meinshausen et al., 2011) to construct long-term cost-effective global greenhouse emission pathways, consistent with long-term climate targets. The cost model uses a least-cost approach involving regional Marginal Abatement Cost (MAC) curves to determine regional mitigation costs, allowing offsetting mechanisms such as international emission trading. The MAC curves account for all major emission abatement options for the energy- and industry-related GHGs, based on the TIMER energy model (see below), as well as non-CO_2 GHGs (Lucas et al., 2007). The MAC curves account for technology change, inertia and removal of implementation barriers.

The **TIMER** model is a global energy-system model that describes the long-term dynamics of the production and consumption of nine primary energy carriers (coal, oil, natural gas, modern biofuels, traditional biofuels, nuclear, solar, wind and hydro) and 5 end-use sectors (industry, transport, residential, services and other) in 26 world regions. The model's behavior is mainly determined by substitution processes of various technologies based on long-term energy prices and fuel preferences. These two factors drive multinomial logit models that describe investments in new energy production and consumption capacity. The demand for new capacity is limited by the assumption that capital is only replaced at the end of the technical lifetime. The long-term prices that drive the model are determined by resource depletion (fossil and renewable) and technology development. Technology development is implemented through endogenous learning curves ('learning-by-doing') that change the investment costs of technologies based on the cumulative installed capacity and exogenous assumptions.

The two MARKAL models **MARKAL China** and **MARKAL India** have similar structure. They are dynamic linear programming energy system optimization models, encompassing extraction, transformation and end-use of energy. The models are driven by a set of demands for energy services and the objective function is the long-term discounted energy system cost. Investment decisions are taken on the basis of least-cost optimization of the energy system, taking into account learning and depletion of resources. The optimizing feature ensures that the model computes a partial economic equilibrium of the energy system (Loulou et al., 1997). The models include nine primary energy carriers (coal, oil, natural gas, hydro, nuclear, wind, solar, bio-energy: MARKAL China also includes geothermal and MARKAL India also includes hydrogen) and five end-use sectors (industry,

[1] All GHG emissions relevant under the Kyoto Protocol (Annex A) are considered. CO_2 equivalent emissions refer to the global warming potential-weighted sum of the six Kyoto gases.

[2] TIMER is part of the IMAGE integrated assessment model (Bouwman et al., 2006), but is here used as a stand-alone energy model.

transport, agriculture, residential (urban and rural), commercial and agriculture). Furthermore, the models include 32 and 46 subsectors, respectively.

The models maintain a vintage capital stock. For each technology, the capacity results from an initial capacity plus previous investments which are still productive. Capital is only replaced at the end of the technical lifetime. However, in MARKAL China some low efficiency technologies (like small coal-fired power plants and iron and steel production) can be forced to be phased out before the end of their life time by setting upper bounds of their capacity in different time periods. Furthermore, for MARKAL China lower bounds for specific technologies like wind, solar power and nuclear power are set in order to consider government's planning targets for the year 2020. Similar or even higher penetration rates are considered beyond 2020.

The models permit specification of exogenous constraints which are offered by the modeller. The constraints typically represent the limits on the market penetration rate of a technology or a group of technologies or the upper or lower limits on demand of a service, e.g. share of a transport mode. The models do not include learning-by-doing and investment costs are assumed exogenous over time.

3. Basic modelling assumptions

3.1. Reference scenario

The models are harmonized to a common reference scenario with respect to the most basic drivers: population, GDP growth, fossil fuel prices and the discount rate. The population projections are in line with the medium variant of UN World Population Prospects (UNDESA, 2009). Globally, the population is projected to increase from around 7 billion people in 2010 to 9.2 billion in 2050, i.e. from 1.2 billion people to 1.6 billion people in India and from 1.4 billion people to 1.5 billion people in China. Urbanization numbers come from the UN World Urbanization Prospects (UNDESA, 2010). Both China and India are projected to urbanize rapidly between 2010 and 2050, i.e. from 47% to 73% in China and from 30% to 55% in India. GDP growth is based on the reference scenario of the OECD Environmental Outlook (OECD, 2012). In this scenario, the global economy is projected to fourfold between 2010 and 2050, growing with on average 2.5%/year. China's economy grows double this rate during the same period with on average 5%/year, and India's economy grows even faster with on average 6%/year. Developments in international fossil fuel prices towards 2035 are taken from the “current policy scenario” of the World Energy Outlook 2010 (IEA, 2010) and kept constant afterwards.[3] Finally, the discount rate is set at 5%/year.

The three models do to some extent assume different energy conversion efficiencies for different technologies. Here, when presenting results on primary energy supply from non-combustible and non-fossil energy sources (wind, hydro, other renewables and nuclear) we convert the electricity production from these sources by using a direct equivalent method, assuming a conversion efficiency of 35% as used in the Global Energy Assessment (GEA, 2012).

3.2. The two 2.9 W/m^2 GHG emission pathways

For the mitigation analysis two GHG emission pathways are constructed with the FAIR model, both reaching 2.9 W/m^2 in 2100. This stabilization level is consistent with medium probability (50% to 66%) of achieving the 2 °C target (Meinshausen et al., 2006; Rogelj et al., 2011). The pathways include all Kyoto gases and unlimited international emissions trading, however, differ in 2020 emission levels and reduction effort between 2020 and 2050.

- The first pathway (hereafter called the least-cost pathway) assumes a least-cost pathway over the whole 2010–2050 period (OECD, 2012)
- The second pathway (hereafter called Copenhagen pathway) implements the conditional, more ambitious 2020 Copenhagen pledges (Den Elzen et al., 2011b),[4] after which emissions reduce gradually towards 2025.[5] Between 2025 and 2050 a constant reduction rate is assumed such that the global cumulative 2010–2050 emissions are equal to those of the least-cost pathway.

Global CO_2-equivalent and energy-related CO_2 emissions of the reference scenario and the two alternative pathways are presented in Fig. 1. Global GHG emissions increase by 75% in 2050 compared to 2010 levels, while energy-related CO_2 emissions increase with 85%. In the two pathways global GHG emissions decrease with 35% and 38% below 2010 levels in 2050, for the least-cost pathway and the Copenhagen pathway, respectively. For the energy-related CO_2 emissions the reductions are 38% and 40%. Fig. 1 also presents the global carbon taxes for the two pathways. The least-cost pathway shows a gradual increase in the carbon tax towards 2050. The Copenhagen pathway shows a much lower carbon tax in 2020 as a result of the lower reduction objective. However, this is followed by a rapid increase in the 2020–2050 period to make up for the postponed reductions, leading to a more than 50% higher carbon tax by 2050 compared to the least-cost pathway.

The difference in 2050 in global emission reductions between the two pathways for the energy-related CO_2 emissions is smaller than for the CO_2-equivalent emissions. The reason is that a higher carbon tax in the Copenhagen pathway in the long run also results in a larger share of non-CO_2 GHG emissions reductions in total abatement as these reductions are relatively cheaper than reductions in the energy system (Lucas et al., 2007). Thus, in the FAIR framework, part of the postponed CO_2 emission reductions is compensated by extra non-CO_2 emission reductions.

4. Climate policy impacts on the energy system

4.1. Energy use and CO_2 emissions in the reference scenario

Without new climate policies, primary energy supply in both India and China is projected to increase considerably (Fig. 2, top). Chinese primary energy use increases strongly towards 2020 in MARKAL China and towards 2030 in TIMER, after which the growth rate gradually decreases. Most of the growth in energy supply comes from fossil fuels, but in MARKAL China also the share of renewables and nuclear energy clearly increases (see Fig. 4).

[3] In the TIMER model fossil fuel prices are modeled endogenously on the basis of long-term supply curves. For the reference scenario these price are calibrated to the exogenous prices. The MARKAL models also make use of supply curves where domestic supplies are modeled as different grades based on extraction costs. Here only the import prices are made consistent to the exogenous prices. In all models the prices still respond dynamically to changes in demand as a result of the introduction of climate policy.

[4] The pledges for non-Annex I countries, including China and India, has been revised in this study due to a different baseline assumptions (OECD, 2012).

[5] When assuming a constant reduction rate between 2020 and 2050, while still aiming for the same 2010–2050 cumulative GHG emissions, the required reduction rate between 2020 and 2025 was found to be infeasible. Therefore, a 2025 emission level was chosen to be the average of the level in the least-cost pathway and in a pathway with a constant reduction rate between 2020 and 2050.

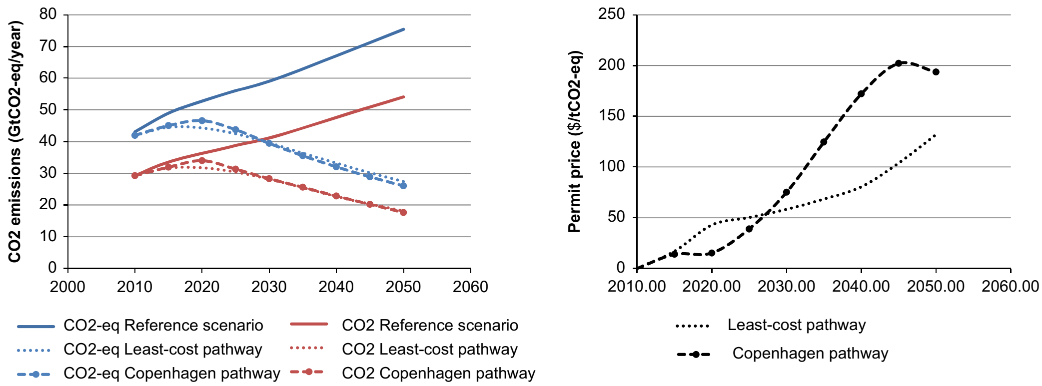

Fig. 1. CO_2-equivalent (excluding land-use CO_2) and energy-related CO_2 emissions for the reference scenario and the two emission pathways (left) and global carbon taxes for the two emission pathways (right) from the FAIR model.

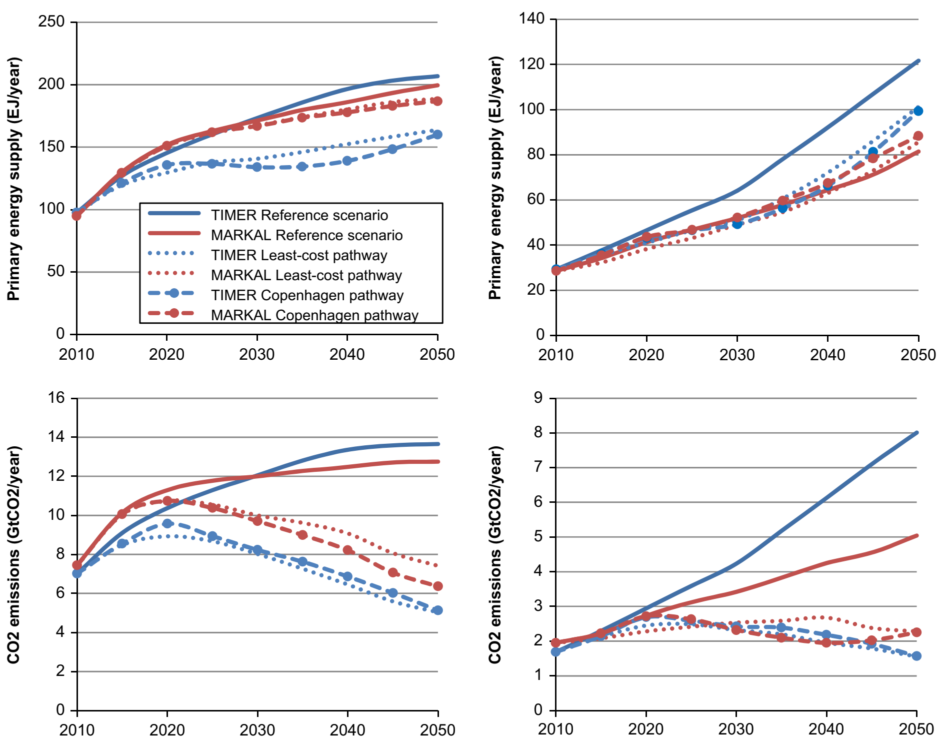

Fig. 2. Total primary energy supply (top) and energy-related CO_2 emissions (bottom) in China (left) and India (right) for TIMER and the two MARKAL models in the reference scenario and the two mitigation pathways.

Primary energy use in India is projected to increase over the whole period, even accelerating after 2030. Differences between TIMER and MARKAL India can be explained by differences in assumptions on energy efficiency improvements and international trade in energy intensive goods. Also in India most of the growth comes from fossil fuels, while in MARKAL India in addition the share of nuclear energy increases significantly. In both countries, fossil primary energy use remains dominated by coal in the reference scenario (around 40% to 50% in 2050). Furthermore, there is a rapid increase in oil use due to growth in the transport sector, and in natural gas use due to growth in electricity production and household energy use.

Due to the large share of fossil fuels in primary energy consumption, the projections of CO_2 emissions are closely related to projections of energy use (Fig. 2, bottom). China is expected to keep high growth of CO_2 emissions up to 2020–2030, only slowly levelling off towards 2050. MARKAL China emissions are lower than those of TIMER as MARKAL China projects a larger share of renewables and nuclear energy. Indian CO_2 emissions are projected to gain pace in growth in 2030, especially in TIMER. Also here, CO_2 emissions in MARKAL India are growing slower as the share of renewables and especially nuclear increases much faster than in the TIMER model. The differences across the models mainly result from different model assumptions, e.g. on the price development of renewables.

4.2. Energy use and CO_2 emission reductions under the two 2.9 W/m^2 pathways

To assess the impacts of the two pathways on changes in CO_2 emissions and the energy systems in China and India, the implications of the two global, uniform carbon tax profiles from the FAIR model (see Fig. 1, right) are analysed in the global energy-system model TIMER and the two national MARKAL energy-system models (Fig. 2). It should be noted that in certain years the primary energy supply in MARKAL India in the mitigation pathways is higher than the reference level due to the direct

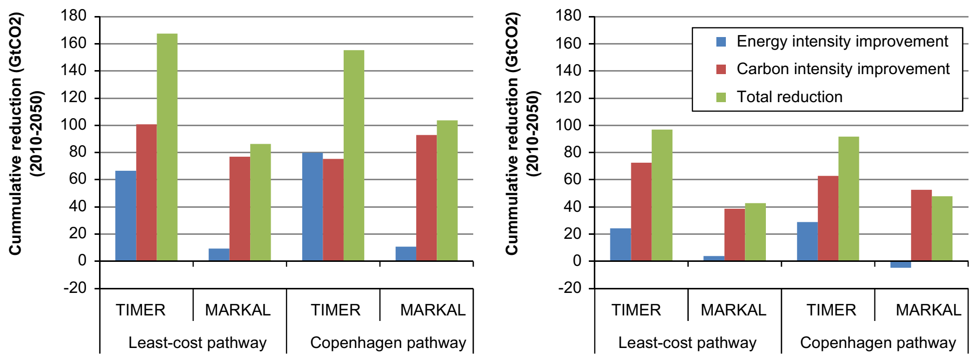

Fig. 3. Decomposition of CO_2 reductions in China (left) and India (right) for TIMER and the two MARKAL models in the two mitigation pathways.

equivalent method used for non-combustible and non-fossil energy sources and energy penalties for CCS.

Using the uniform carbon taxes, both MARKAL models show fewer reductions towards 2050 than the TIMER model. Underlying causes include differences in model type and assumptions for renewable energy costs. Furthermore, in the two MARKAL models, the transport sector does not respond to a carbon tax alone and requires changes from outside, addressing urban form, modal shares, travel demand, etc. These can be introduced exogenously, but not in a scenario linked to only carbon taxes. In the TIMER model, travel demand, energy intensity and the energy mix in the transport sector responds much stronger to a carbon tax resulting in much higher emission reductions. See Section 4.5.2 for a discussion of the transport sector.

In the case of India, CO_2 emissions in the reference scenario and the Copenhagen scenario are nearly similar till 2020. This implies that the Copenhagen commitment does not impose much additional reduction requirements compared to the reference scenario. This is in line with earlier analysis (Den Elzen et al., 2011a; Shukla and Dhar, 2011).

Fig. 3 presents a decomposition of cumulative emission reductions in energy intensity improvements (the ratio between energy use and income) and the carbon intensity improvements (the ratio between emissions and energy use). The figure shows large difference between the two model types. See also above discussion.

In the TIMER model clear differences between China and India, but also between the two mitigation scenarios can be noted. The difference between China and India can be explained by projected growth in energy demand. Technologies are only replaced after their technical lifetime. The slow-down of growth in energy demand in China implies a decreasing demand for new facilities. This limits flexibility in the supply sector, and increases the importance of energy efficiency improvements on the demand side (see also Van Ruijven et al., 2012a). In India, growth in energy demand accelerates after 2030 and thereby the demand for new facilities, thus increasing the decarbonisation potential. The difference between both mitigation scenarios can be explained by the postponement of mitigation action beyond 2020 in the Copenhagen pathway. Due to postponing mitigation action more fossil-powered plants will be built on the short-term, with a technical lifetime around 30 years. As capital is only replaced at the end of the technical lifetime, this reduces the decarbonisation potential towards mid-century. Furthermore, postponing mitigation action also reduces learning-by-doing, making wind and the solar power more expensive in the long-term.[6] Both effects favor energy efficiency improvements over decarbonisation.

In both MARKAL models, the relative contribution of cumulative emission reductions from improving the energy intensity is much smaller than from improving the carbon intensity, as substantial energy conservation and efficiency improvements measures already exist in the reference scenario. This includes energy efficiency improvement from economic structure adjustment. In MARKAL each technology class (e.g., coal based electricity generation, gas based electricity generation, petrol cars, etc.) is represented through a grade wise structure to characterize the different technology variants. Each technology grade is assumed to become more efficient in time and this information about technological learning is included in the model database exogenously. In addition the capital costs for technology grades representing newer technologies (which are more efficient) also decline more rapidly compared to the matured but relatively inefficient technologies.[7] Therefore, there is little scope for additional efficiency improvements in the climate policy scenarios. Hence, the differences in efficiency improvement between the two mitigation scenarios are also small.

4.3. Climate policy costs

Table 1 presents the direct costs of climate policy, measured as 2010–2050 cumulative discounted abatement cost relative to cumulative discounted GDP. The FAIR model determines the climate policy costs as the area under the MAC curve (constructed with the TIMER model). The two MARKAL models determine climate policy costs as the difference of the sum of the discounted investments and operational costs between the mitigation pathway and the reference scenario.

In all models, the Copenhagen pathway results in significantly higher abatement costs than the least-cost pathway, as was already concluded in global studies (Den Elzen et al., 2010; Van Vliet et al., 2012). The global carbon tax for the least-cost pathway is considerably higher than for the Copenhagen pathway until 2030 (Fig. 1). This leads to early investments under the least-cost pathway, which pick-up low hanging fruits and spurs early investments in low carbon infrastructures and prevents lock-ins. It should be noted that, in the case of MARKAL India, the climate policy costs are relatively low in both mitigation scenarios since the reference scenario already includes sizable investments in renewables and energy efficiency.

The differences between the two mitigation pathways are higher in the two MARKAL models, than in the FAIR model.

[6] Learning-by-doing is only included in the TIMER model and not in the two MARKAL models.

[7] For example in MARKAL India transformation efficiency of subcritical pulverized coal is expected to improve from 33% in 2010 to 38% in 2050 and for IGCC technology (a more efficient technology) is expected to improve from 40% to 48% during the same period and with a faster decline in capital costs. The combined effect is that the overall transformation efficiency for coal based power achieves a fast improvement.

Although carbon taxes are the same in both models, these differences can be explained by two reinforcing model mechanisms. In the FAIR model, the two pathways have equal 2010–2050 cumulative CO_2 equivalent emission reductions, with a slightly higher share of non-CO_2 emission reductions in the Copenhagen pathway (see Section 3.2 and Fig. 3). The lower cumulative CO_2 emission reductions thus partly compensate for the higher carbon tax. It should be noted that the climate policy costs presented for the FAIR model in Table 1 only account for CO_2 emission reductions. In the two MARKAL models there is no interaction with non-CO_2 GHGs. Here, differences between both pathways result from differences in the carbon tax profiles. The sharply increasing carbon tax profile of the Copenhagen pathway results in slightly higher cumulative emission reductions in both MARKAL models, leading to higher cumulative costs.

4.4. Changes in fuel mix

Fig. 4 shows the aggregate fuel mix for the different scenarios. Towards 2020 the fuel mix in the mitigation scenarios is somewhat similar to the reference scenario in all models. Emissions are reduced mainly through energy efficiency improvement or fuel switching from coal to gas fuelled power plants. In MARKAL China fossil fuels with CCS are the main source of emission reductions.

In 2050, primary energy use under the two mitigation scenarios has completely changed compared to the reference scenario. The use of fossil fuels has been reduced significantly – especially in India – while renewables, nuclear energy and fossil fuels with CCS have gained importance. In the TIMER model a significant share of reductions comes from increased use of biofuels, while non-biomass renewables increase much less. The latter can to a large extend be related to the dynamics of integrating variable energy sources in the TIMER model. As the model requires spinning reserve and additional capacity for increasing wind and solar energy, their market shares stabilize around 20%. Furthermore, hydro energy is fixed through an exogenous scenario and will not change under mitigation scenarios. In both MARKAL models non-biomass renewables and fossil fuels in combination with CCS are by far the most important source for emission reductions. Both China and India have high coal reserves. As the MARKAL models optimize over the supply curve and not the equilibrium fuel prices, supply of coal is favorable. Besides, both countries are sizable future importers of oil and also gas (see Section 5.2). Therefore coal fired power plants with CCS would help 'Energy Security' concern under CO_2 mitigation scenarios (Garg and Shukla, 2009).

In the TIMER model, due to the much lower carbon tax in the Copenhagen pathway in 2020, CCS is used later than in the least-cost pathway. However, due to the fast increasing carbon tax in the 2020–2050 period the shares in 2050 are rather similar. Towards 2050, the share of biofuels increases faster in the Copenhagen pathway and the share of nuclear energy in the least-cost pathway. In both MARKAL models, from 2035 onwards the share of fossil fuels is much larger in the least-cost pathway and only starts dropping significantly around 2040, while in the Copenhagen pathway the share of fossil fuels already drops significantly around 2030. The difference is mainly compensated by renewables.

For China and India, the TIMER dynamics with respect to the timing of technologies are similar. However, reduction of fossil fuel use is much smaller in China. The same holds for biofuels and nuclear power, whose shares are higher in India. In China, in all models the share of fossil fuels is larger in the least-cost pathway over the whole 2020–2050 period. The difference is compensated by higher shares of efficiency improvements and CCS in TIMER and nuclear energy in MARKAL China. In India in TIMER the two pathways show almost similar results. In MARKAL India the shares of CCS and nuclear are much larger in the Copenhagen pathway.

Table 1
Cumulative discounted costs of climate policy relative to cumulative discounted GDP.

		Mitigation costs for the least-cost pathway (%-GDP)	Mitigation costs for the Copenhagen pathway (%-GDP)	Cumulative discounted GDP (trillion \$)[a]
China	MARKAL	0.30	0.94	190
	TIMER	0.57	0.70	235
India	MARKAL	0.10	0.26	76
	TIMER	0.89	1.14	78

[a] The GDP growth rates were harmonised among the different models; not the 2010 levels. As the 2010 levels differed slightly per model, cumulative 2010–2050 GDP also differs.

4.5. Sectoral changes

Energy use is globally almost equally shared between three main sectors (industry, services and domestic, and transport), while electricity production accounts globally for around 43% of total energy related CO_2 emissions. Current shares of energy use in the transport sector in China and India are much smaller than the global average (Van Sluisveld et al., submitted for publication). Furthermore, CO_2 emissions from electricity production are much higher, i.e. around 48% in China and 55% in India. Towards 2050 the shares in energy use in China and India move more towards the global average with faster increasing energy use in the transport sector than in all other sectors. Furthermore, towards 2050 CO_2 emissions from the power sector grow above 50%

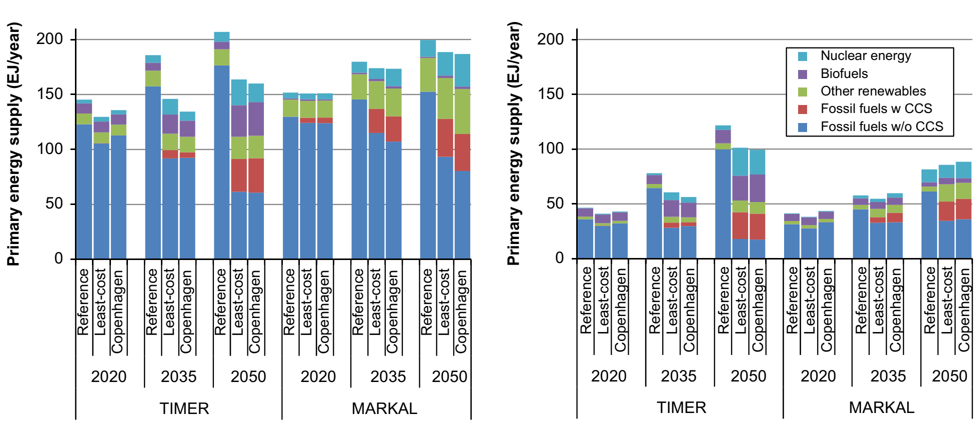

Fig. 4. Total primary energy use in China (left) and India (right) in the reference scenario and the two mitigation scenarios for TIMER and both MARKAL models (note that renewables and nuclear energy are shown in primary equivalents).

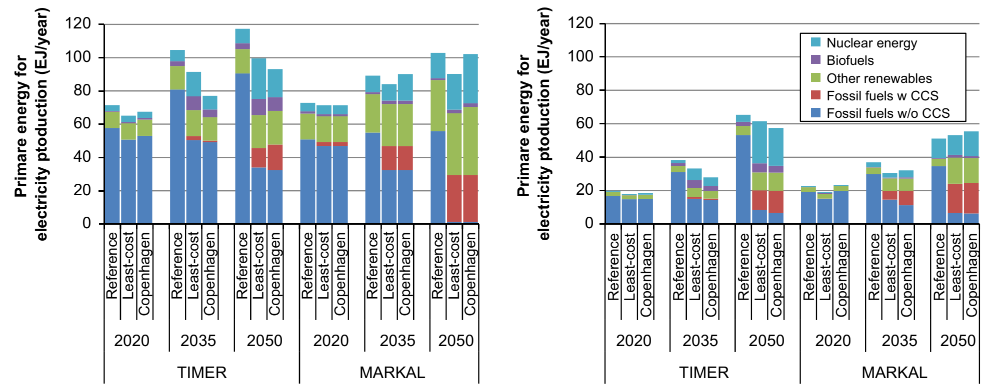

Fig. 5. Primary energy use in the power sector in China (left) and India (right) in the reference scenario and the two mitigation scenarios for TIMER and both MARKAL models (note that renewables and nuclear energy are shown in primary equivalents).

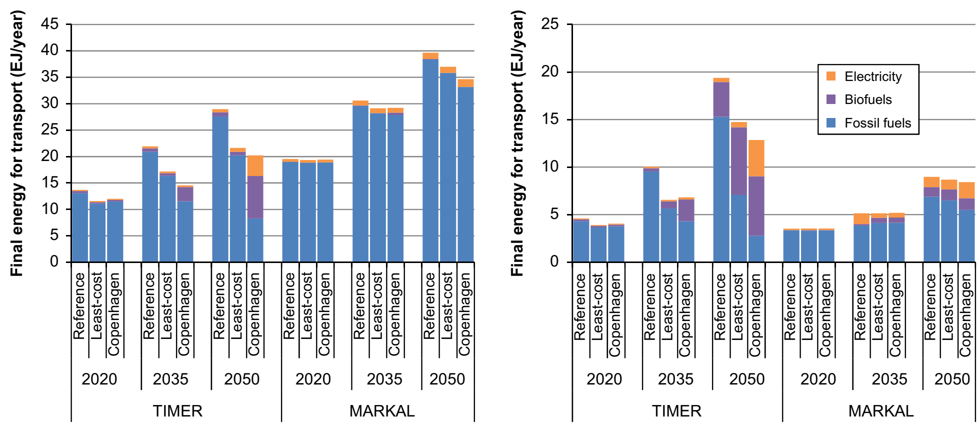

Fig. 6. Energy use in the transport sector in China (left) and India (right) in the reference scenario and the two mitigation scenarios for TIMER and both MARKAL models.

globally and for China and India even above 60%. Thus, the power sector plays a key role in future energy use and mitigation of CO_2 emissions (Fig. 5), while also the increasing CO_2 emissions from the transport sector become an important source of emission reductions (Fig. 6).

4.5.1. Electricity production

In the reference scenario, electricity production follows a similar pattern as primary energy use; both are dominated by fossil fuels. However, both MARKAL models already show strong decarbonisation in 2050, with more than 45% of electricity production coming from low-carbon sources in China, and 30% in India. In TIMER this is around 20% in both countries.

The mitigation scenarios show for 2050 a completely different fuel mix compared to the reference scenarios. For China in the TIMER model, electricity production from fossil fuels is reduced to present-day levels and replaced by fossil CCS, bio-energy, nuclear energy and renewables. Energy efficiency has also increased by almost one-third. In MARKAL China fossil fuel use without CCS is almost completely eradicated and replaced by CCS and renewables and nuclear energy. Use of bio-energy and energy efficiency improvements is small. India shows a decrease in fossil based power generation in total energy production to only 10% in both TIMER and MARKAL India. In TIMER this due to a combination of energy efficiency improvement, fossil fuels with CCS, a large share of nuclear energy and some renewables. In MARKAL India the most important mitigation sources are CCS and renewables. The variation in the future portfolio choices among nuclear, CCS and non-biomass renewables between TIMER and the two MARKAL models are due to differences in the cost structures of the different technologies.

4.5.2. Transport

In the reference scenario energy use in the transport sector grows much faster in China and India than in the other sectors, with shares in total energy use almost doubling between 2010 and 2050. Most of this growth comes from fossil fuels, i.e. oil and natural gas. Under the two mitigation scenarios the energy use for transport decreases, and so does the share of fossil fuels. Similar to the power sector, in both China and India, fossil fuel use reduces more in the Copenhagen pathway than in the least-cost pathway.

Biofuels are an important mitigation option in the transport sector in India in both models and both mitigation scenarios, while in China they only become important in the Copenhagen pathway in the TIMER model. Because in the TIMER model bio-energy use has strong lock-in dynamics, in the least-cost pathway the power sector is the first to use a large share of available feedstock, whereas in the Copenhagen pathway, biofuels for transport are more favorable. Biofuels is a stated policy objective of India to improve energy security, improve rural livelihoods and reduce dependence on fossil fuels (MNRE, 2009). In MARKAL India, land for biofuel production is given the priority only after land requirements for food production, non-agricultural uses and forests are met (Shukla et al., 2010). Increasing food demand[8] and a stated policy to increase forest cover from current 23% to 33% of land area, limit land available for biofuel cultivation (see

[8] Increase in food demand is expected due to an increase in population, increase in per capita food consumption and diversification of food basket.

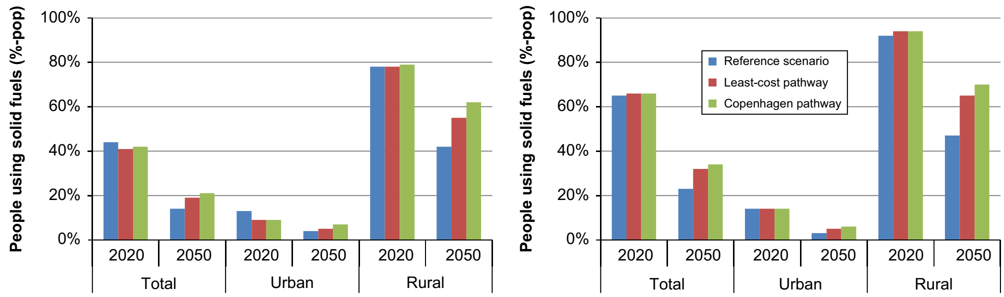

Fig. 7. Traditional fuel use in urban and rural households in China (left) and India (right) in the reference scenario and the two mitigation scenarios for the TIMER model only.

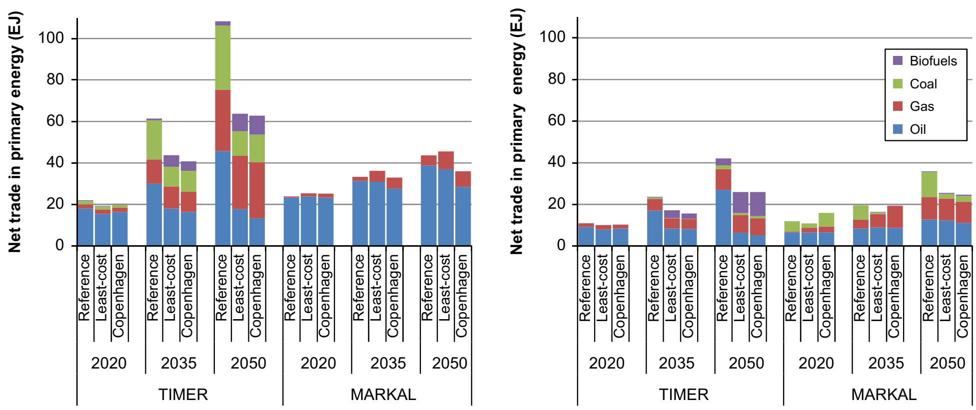

Fig. 8. Net trade in fossil fuels and biofuels in China (left) and India (right) in the reference scenario and the two mitigation scenarios for TIMER and both MARKAL models.

Figure 10 in Shukla et al., 2010). Therefore a large part of the biofuel supply comes from imports (see Section 5.2).

A transition to electric transport is another important mitigation option in the transport sector, especially in India. Electric vehicles become competitive against petrol and diesel driven vehicles already by 2035, even in the reference scenario. However, the high carbon taxes in the two mitigation scenarios act as a barrier for the penetration of electric vehicles in the transport sector. Further decarbonization of the electricity sector under the two mitigation pathways reduces this barrier, resulting by 2050 in a higher share of electric transport than in the reference scenario.

5. Trade-offs and co-benefits

5.1. Traditional energy use

People with low incomes depend heavily on solid fuels (coal, fuelwood or dung) used on inefficient stoves to fulfill their daily energy needs. Generally, households switch from traditional fuels to cleaner fuels (kerosene, LPG and electricity) when their welfare level increases (Van Ruijven et al., 2008). If households grow wealthier their fuel choice change due to increasing capital availability– allowing for more capital intensive fuel types – and more attention for the disadvantages of traditional fuels, such as indoor air pollution causing significant health loss and time spent on fuel collection. If a climate policy is introduced through a carbon tax on fossil fuels, these fuels become more expensive, making it more difficult for poorer households to switch to cleaner fuels (assuming that traditional fuels, excluding coal, are not affected by the carbon tax). Depending on the actual measures implemented this could create a potential trade-off between climate policy and indoor air quality (Van Ruijven, 2008; Van Ruijven et al., 2011).

This effect is visible in Fig. 7, in terms of the shares of the population (total, urban and rural) using solid fuels (here only coal and fuelwood) in the reference scenarios and the two mitigation pathways. The results are only shown for the TIMER model, as both MARKAL models do not report traditional energy use. In all three scenarios the population using solid fuel decreases steadily over time. However, this decrease is slower in the mitigation scenarios, especially in rural areas, where the differences in 2050 with the reference scenarios can amount to as much as 13 to 20 percentage-points in rural China and 18 to 23 percentage-points in rural India in 2050, representing 51 to 77 million people in China and even 127 to 160 million people in India. In China, climate policy can have a small positive effect for urban households, where households depend more on coal than fuelwood, as is the case in rural households.

5.2. Energy security

Net trade in primary energy sources is generally seen as an indicator for energy security (Fig. 8). Both China and India are net energy importers, mainly with respect to oil and gas. In their reference scenarios, total imports increase further as well the imported share of total use. For oil these shares even reach almost 100% in 2050 in both countries. In the mitigation scenarios total imports decrease, especially in TIMER and MARKAL India. The decrease is almost 40% in both countries in the TIMER model by 2050; the decrease in MARKAL India is 60%. The latter is mainly the result of strongly decreasing imports of coal. In MARKAL China energy imports can increase slightly due to climate mitigation as the result of fuel switching from local coal to imported gas. These decreasing imports can be interpreted as a co-benefit of climate policy, as decreasing energy imports is generally interpreted as an increase in energy security.

6. Discussion and conclusions

This paper provides a multi-model analysis of two scenarios that describe an early action versus delayed response in global climate mitigation for China and India, addressing total cumulative abatement costs and changes in the energy systems. The scenarios follow a least-cost pathway and a pathway that postpones ambitious mitigation action, starting from the Copenhagen Accord pledges. Both pathways have similar 2010–2050 cumulative greenhouse gas emissions. Emission reductions in China and India for the two emission pathways were induced by assuming a uniform global carbon tax. The analysis does not take into account an effort-sharing approach to distribute the climate policy costs between countries and therefore does not refer to the bearing of mitigation cost, but solely discusses the national costs related to changing the energy system.

Both pathways require significant changes in the energy systems of China and India, reducing the use of fossil fuels and increasing importance of renewables (including biofuels), nuclear and fossil energy with CCS. Differences between both pathways can be explained from the short and long-term differences in carbon taxes, capital stock turnover and technological learning. The analysis shows that postponing mitigation action based on the pledges increases the dependence on fossil fuels on the short-term, increases lock-in effects in less energy efficient technologies, and induces faster and deeper reductions on the long-term to compensate for the lower short-term emission reductions. Furthermore, postponing mitigation action implies much higher cumulative mitigation costs, especially in the national models where compensation by non-CO_2 emission reductions is not included. This urges China's and India's electricity system to shift away from fossil dependence before there is a lock-in into the electricity mix, as in the reference scenario. The lock-in would be both in the carbon content of fuel as well as locations of power plants which may not facilitate post-facto economical use of CCS.

Distinct differences between the results for the two model systems (TIMER and MARKAL) and both countries (China and India) can be noted. In the TIMER model there is a significant contribution in the two mitigation pathways for both energy intensity improvements and carbon intensity improvements. The shares for carbon intensity improvements are larger in India and in the least-cost pathway. The two MARKAL models primarily reduce emissions through carbon intensity improvements for both China and India and the two pathways. In the TIMER model a significant share of reductions comes from fossil fuels in combination with CCS and increased use of biofuels, while non-biomass renewables increase much less. In both MARKAL models non-biomass renewables and fossil fuels in combination with CCS are by far the most important source for emission reductions.

The differences between the two models types relate to the dynamics included in the models. As the TIMER model includes learning-by-doing, early action induces more rapid technology development and lowers the costs of future technologies. With respect to energy efficiency, the TIMER model includes the possibility of energy service demand reduction, thereby increasing the potential for energy intensity improvements. For both MARKAL models, substantial energy conservation and efficiency improvements measures already exist in the reference scenario, leaving little scope for additional efficiency improvements in the climate policy scenarios.

The differences between China and India can partly be explained from the capital stock turnover of power production capacity. As electricity production capacity is only replaced at the end of its technical lifetime, the outline of the power system in 2050 is very much determined by the optimal technology choice at the time of rapid growth. The growth in the Chinese power production takes mainly place between now and 2030, while the rapid growth phase in India is between 2020 and 2050. As a result, in TIMER by 2050 China still has a significant share of conventional coal power plants in the mitigation scenarios. In MARKAL China, however, this is less of a constraint, as all fossil power plants are by then replaced by fossil plants that include CCS. In both TIMER and MARAL India, by 2050 the share of non-CCS fossil power production is down to only 10%.

A sensitivity assessment of technologies (in terms of future cost structure) may help improve the understanding of these results. Besides, strategic global RD&D co-operation on low carbon technologies may help to enhance the share for those technologies that are sensitive to future cost structures.

It should be noted that the calculations focus on the 2010–2050 period only, despite the long-term target that has been set. Clearly, reaching the climate target requires further reductions after 2050, while the state of the energy systems in 2050 constrains 2050–2100 reductions. Therefore, potentially new technologies with negative emissions – such as the use of bio-energy combined with carbon capture and storage – might be required beyond 2050.

Finally, climate policy strongly relates to other energy-related issues, such as air pollution and energy security. Imposing a carbon tax potentially makes modern energy source, such as kerosene, LPG and electricity – fuels that are less associated with indoor air pollution than traditional biomass or coal – more expensive, thereby making it more difficult for poorer households to switch to these cleaner fuels. This is especially the case in rural areas. On the contrary, the transition to renewables induced by climate policy reduces the import dependence on fossil fuels. In China and India this primarily relates to oil imports, while on the short term the imports of gas might slightly increase. Furthermore, reduced fossil fuel imports are partly compensated by increasing imports of biofuels. This is especially the case in India where most agricultural land is used for food production and forests and biofuel are imported from less constrained countries in Southeast Asia, Africa and South America.

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