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# Global Fossil Energy Markets and Climate Change Mitigation – an analysis with REMIND

*Nico Bauer*[1]*, Ioanna Mouratiadou, Gunnar Luderer, Lavinia Baumstark, Robert J. Brecha, Ottmar Edenhofer, Elmar Kriegler*

## Abstract

We analyze the dynamics of global fossil resource markets under different assumptions for the supply of fossil fuel resources, development pathways for energy demand, and climate policy settings. Resource markets, in particular the oil market, are characterized by a large discrepancy between costs of resource extraction and commodity prices on international markets. We explain this observation in terms of (a) the intertemporal scarcity rent, (b) regional price differentials arising from trade and transport costs, (c) heterogeneity and inertia in the extraction sector. These effects are captured by the REMIND model. We use the model to explore economic effects of changes in coal, oil and gas markets induced by climate-change mitigation policies.

A large share of fossil fuel reserves and resources will be used in the absence of climate policy leading to atmospheric GHG concentrations well beyond a level of 550ppm $CO_2$-eq. This result holds independently of different assumptions about energy demand and fossil fuel availability. Achieving ambitious climate targets will drastically reduce fossil fuel consumption, in particular the consumption of coal. Conventional oil and gas as well as non-conventional oil reserves are still exhausted. We find the net present value of fossil fuel rent until 2100 at 30tril.US$ with a large share of oil and a small share of coal. This is reduced by 9 and 12tril.US$ to achieve climate stabilization at 550 and 450ppm $CO_2$-eq, respectively. This loss is, however, overcompensated by revenues from carbon pricing that are 21 and 32tril.US$, respectively. The overcompensation also holds under variations of energy demand and fossil fuel supply.

***Keywords:*** *Climate change mitigation, fossil resource rent, price formation mechanism*

***JEL***: D72, Q40, Q54

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This study comes with Supporting Online Material available at: http://www.pik-potsdam.de/members/nicolasb/bauer-etal-2013-rosesi-som-vpreprint.docx

# 1. Introduction

The interaction of climate policy and fossil fuel markets is of great interest for climate and energy economists and for policy makers. Climate change stabilization imposes limitations on $CO_2$ emissions from fossil fuel combustion, thus leading to a re-allocation of the use and prices of fossil fuels. A comprehensive assessment of the macroeconomic and energy sector consequences of policy action requires a thorough quantification of energy market effects. Global mitigation costs and distributional effects largely depend on baseline assumptions of energy demand (GDP, population, technological change) and fossil fuel supply that are highly uncertain (Weyant 2001).

Climate change mitigation costs are constituted to a large part by the opportunity costs of not using fossil energy, but substituting them with alternative energy supplies, increased energy efficiency or reduced economic activity. Evaluation of climate change stabilization costs must also consider fossil fuel market re-allocation, i.e. the endogenous changes to fossil fuel prices and usage induced by climate policies (Harberger 1968; Grubb 2001).

The IPCC analyzed sectoral effects of emissions mitigation (Barker et al. 2007; Gupta et al. 2007), mainly focusing on short- to medium-term mitigation policies. The assessment was based on fossil energy prices that were – in accordance with observations of that time – much lower than those witnessed since 2003. More recent model comparison exercises found relatively low global mitigation costs for a range of long-term climate change mitigation targets and assumptions of technology availability (Van Vuuren et al. 2009; Clarke et al. 2009; Edenhofer et al. 2010; Luderer et al. 2012a); few studies have focused on the role and uncertainties of fossil energy markets (Perrson et al. 2007; IEA 2009; Rosenberg et al. 2010; Lüken et al. 2011; Nemet and Brandt 2011). These confirm that the distributional effects for oil- and gas-rich countries are quite small (some even positive), but the analyses did not include a full account of fossil energy markets; e.g. Perrson et al. (2007) note the weakness of the model used to predict oil prices being much lower than the 60US$/bbl of that time.

In the energy economics literature, resource abundance and the future of energy markets are highly disputed. The “optimistic” perspective is usually captured by a cumulative supply cost function that assumes higher prices will make more deposits competitive (Aguilera et al. 2009). This concept implicitly assumes the theorem of Herfindahl (1967): deposits are fully exhausted in the sequence of their increasing marginal costs, and marginal costs always equal average costs. “Pessimists” following the Hubbert-approach assume that a given amount of fossil fuels from a single deposit is available and a set of shape parameters, like the production decline rate, determines the future depletion path, but prices have only limited influence (Sorrell et al. 2010). “Optimists” and “pessimists” disagree strongly on the interrelationship between prices and the changes in production.

Jakobsson et al. (2012) attempt a synthesis. They argue that the cumulative supply cost function is not sufficient for determining fossil fuel prices. Inertia, imposed by flow rate constraints that limit the decline of extraction from each deposit, leads to the simultaneous exhaustion of various deposits. Static price formation drives the market price above the highest marginal costs of all open deposits, which in turn exceeds total average costs and implies producer rents.

Regional differentiation of fossil resource endowments and transportation costs also require careful consideration in the price formation mechanism. The home-bias effect (Obstfeld and

Rogoff 2000), leads to regional price differences and diversity of energy use across regions. The global energy system's development as well as mitigation potentials strongly depend on regional diversification.

For the present study the representation of fossil extraction in the global energy-economy-climate model REMIND was extended by the supply dynamics and home-bias effect. The sensitivities of baseline assumptions are tested to produce a novel set of baseline and climate change stabilization scenarios. The modeling approach comprises fundamental economic, technical and geological factors of fossil energy supply. When presenting results we will also briefly discuss other related factors such as volatility and current high prices, although these are not the major focus of the present paper.

We address three research questions. What is the global long-term development of fossil fuel markets under different baseline assumptions and what is the impact of climate change mitigation policies? How large are the fossil resource rents and how do they depend on baseline assumptions and climate policies? How does the change in fossil rents compare with the revenues from carbon pricing?

Section 2 introduces the methodology regarding the general modeling framework and the modeling approach of the fossil fuel markets in particular. Section 3 gives an overview of the design of the scenarios, reports the results and puts them into perspective with the literature. Section 4 draws conclusions and provides an outlook on further research.

## 2. Methodology

This section provides (i) a general overview of the REMIND model and (ii) a more detailed treatment of the fossil fuel extraction sector. The Supporting Online Material of the Synthesis Paper (Kriegler et al., this issue) provides more details. The current version of REMIND builds on previous model versions (Bauer et al. 2012a, b; Luderer et al. 2012b).

REMIND is a global multi-regional model of the economy, energy sector and the climate system that computes long-term general equilibrium pathways until 2100. In each region a detailed bottom-up energy sector model is embedded in a Ramsey-type optimal growth model with a top-down production and a social welfare function. The hard-link between the two sectors and the inter-temporal structure guarantees simultaneous equilibrium on all markets for energy, capital, goods and labor, with perfect foresight (Bauer et al. 2008). The energy sector demands primary energy carriers (including fossil fuels, nuclear, renewables, etc.) that are converted into final energy carriers; these are then supplied to the macro-economic sector, which in turn uses them in combination with capital and labor to generate GDP. GDP is allocated to investments, energy expenditures and household consumption. Households maximize intertemporal welfare as the sum of discounted utilities of private consumption using a pure rate of time preference of 3%/yr. Hence, the trade-off between current and future consumption is balanced by choosing investments and the use of resources including fossil fuels. Trade in goods, fossil energy, uranium and emission permits between regions is modeled. The Negishi approach computes market equilibria for these goods subject to constraints on the inter-temporal balance of payments of each region and import-export constraints for the world market in each period. The capital accounts are balanced, since net foreign assets across regions always sum up to zero.

The energy sector in each region represents capacity stocks for the conversion of energy carriers. Investments expand the capacity stocks, but compete with household consumption.

Several non-linearities are considered including endogenous technological learning, adjustment costs of ramping up specific capacities, and grid and storage penalties for wind and solar electricity generation.

GHG and aerosol emissions from the energy sector are joint products of energy production and conversion processes. Carbon Capture and Storage (CCS) technologies can reduce emissions from fossil fuel use and even remove carbon from the atmosphere if combined with bio-energy. GHG emissions not originating from the energy sector are subject to exogenous baseline emissions. Non-$CO_2$ GHG emissions from the energy sector add to these baselines. Marginal abatement cost curves (MACC) represent the emission reduction potentials. Aerosol emissions from fossil fuel combustion are endogenously linked to activity levels with exogenous assumptions about pollution controls leading to, e.g. desulphurization.

Fossil fuel extraction sectors utilize coal, oil and gas endowments in each region. Endowments are subdivided into different cost grades. In addition to the long-term supply functions (Fig. S1) additional features characterize the fossil extraction sector in REMIND. The supply flow from each grade can grow no more than 10% annually and generally not decline more than 15%/yr. However, low cost grades of oil and gas exhibit smaller decline rates as reported in Table S1 (IEA 2008, 2009). The smallest decline rate of 3.4%/yr is assumed for the lowest cost grade of oil in the Middle East and North Africa (MEA) region. Higher cost grades, for instance unconventional oil and gas, show higher decline rates, since extraction requires stimulation techniques.

In addition to these hard constraints, changes of supply flows from each grade lead to adjustment costs that are quadratic in the annual rate of output change. These short-term annual supply curves are combined with the long-term cumulative supply functions. Large relative changes in annual output lead to large relative mark-ups over the long-term extraction costs. For a change of annual output of 5% , the mark-up is also 5%, i.e. the elasticity equals one. Below (above) this value the elasticity is less (higher) than one due to the quadratic form. We have chosen relatively optimistic values (Dahl and Duggan 1998; Krichene 2002; Askari and Krichene 2010) for two reasons. First, REMIND operates at five year time steps, but supply responses are usually estimated for shorter periods. Second, estimates of supply elasticities post-2000 were found smaller, even negative, compared to pre-2000 elasticities (Askari and Krichene 2010). We note that the empirical literature on the inertia of fossil fuel supply is limited, though the ramp-up of new technologies is crucial.

The extraction of fossil fuels is accompanied by GHG emissions. Methane emissions intensities of gas and coal extraction can be reduced from historical values s according to a MACC. For non-conventional oil the carbon intensity increases with decreasing fuel quality and lower energy return on energy invested (Brandt 2009; Charpentier et al. 2009).

Transport costs of fossil fuel trade are differentiated for exports and imports. Exporters incur costs for transporting the goods to the border or a harbor, where the fuel enters the global market and exporters receive the world market price. Importers pay the costs for inter-regional transportation and carry the burden of losses for transportation including liquefaction of natural gas. Table S2 summarizes the trading cost parameters. The import distances of each region are measured by taking into account the distances of exporting countries to the import points (like main harbors) of the importing regions.

# 3. Results

The results of the various scenarios are presented in three steps. The Default Baseline scenario without mitigation is discussed first. Section 3.2 analyzes the sensitivity of baseline assumptions without climate policies. Third, the impact of climate policies is analyzed assuming a 550ppm $CO_2$-eq “not-to-exceed” target (called 550-e) and a 450ppm $CO_2$-eq target with overshoot before 2100 (450-e), with both policies being analyzed for different baseline assumptions. The temporary overshoot is allowed in the stronger 450-e scenario because otherwise the long-term target is not feasible. See Table S3 for an overview of scenarios.

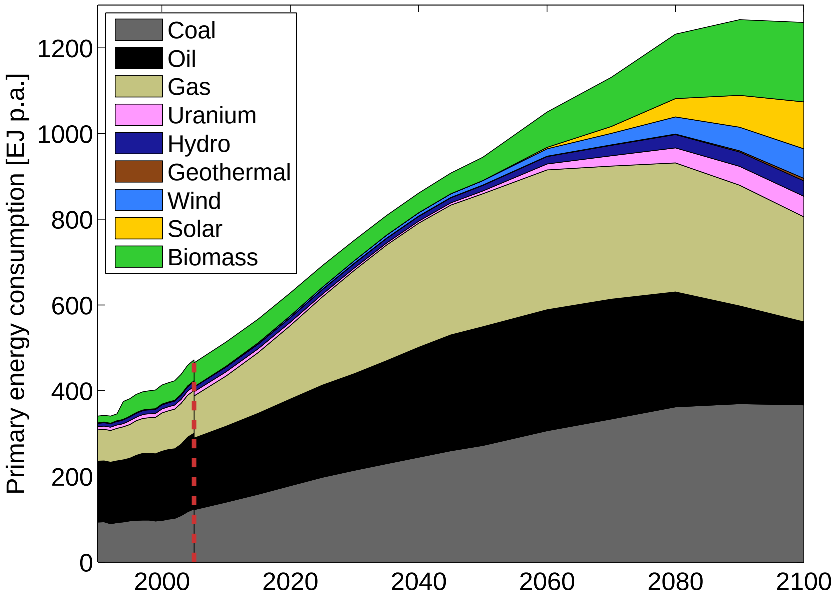

**Fig. 1:** Historical development (1990-2005) of primary energy consumption in direct equivalents and the default baseline (2005-2100). Historical data is taken from IEA (2007).

## 3.1 The Default Baseline

The Default Baseline scenario applies the reference case assumptions (intermediate levels of population, economic growth and fossil fuel availability) and does not impose limitations on atmospheric GHG concentrations. Two general features characterize the development of the energy sector.

First, total annual demand for final energy carriers grows over the 21st century from 365EJ in 2010 to 890EJ in 2100 (see Fig. S3&4). This growth comes along with modernizing energy use by decreasing the share of solid fuels and non-transportation liquids and increasing the share of gases, transportation fuels and electricity. Second, developing countries’ share of final energy demand increases due to the assumed convergence of per-capita incomes.

Second, global annual primary energy production shown in Fig. 1 grows from 515EJ in 2010 to 1260EJ in 2100. Fossil fuels play the dominant role until mid-century; thereafter the share of non-fossil fuels increases to supply electricity. Coal is partially reallocated from the electricity sector to the production of synthetic liquids for the transportation sector to substitute for crude oil after its peak. Gas and coal use show strong variations between regions due to transportation costs and relative abundance of domestic primary energy supplies.

The overall growth and stabilization in fossil fuel use is driven by structural changes between oil, coal, and gas. The total output of oil grows steadily until 2060, peaking at 280EJ p.a. Coal output grows rapidly, at an average rate of 2.2% p.a. from 2010 until 2030. Average annual growth slows to 0.8% over the rest of the century as non-fossils gain share in the electricity sector and coal use is shifted towards the supply of liquid transportation fuels. Natural gas output grows at 3.7%/yr as it is increasingly used in the electricity sector until 2030. Afterwards gas output growth slows and production peaks at 325EJ in 2060. The cumulative consumption of coal, oil and gas from 2010 to 2100 is 26ZJ, 23.2ZJ and 25.5ZJ, respectively, leading to total carbon emissions of 5780 $GtCO_2$ (see also Fig. S5).

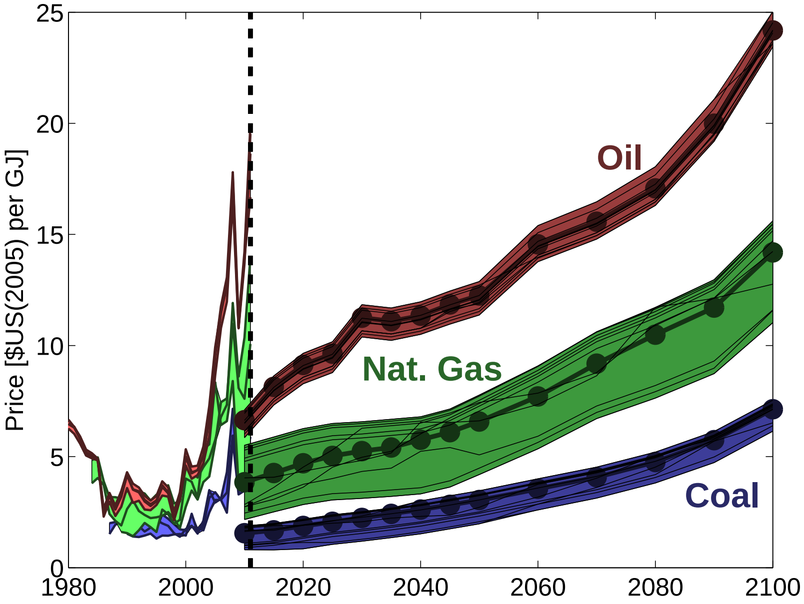

**Fig. 2** Historical development (1980–2011) and future fossil fuel prices (2010–2100) in the Default baseline. The regional prices are indicated by the individual solid lines; areas show the variations. Solid thick lines are global average prices. Historical prices (BP 2012) for coal and gas for different regions are only shown for few import countries (US, Europe and Japan). Since the scenarios cover all regions, the spread in future prices is larger

The corresponding scenarios of fossil fuel prices are shown in Fig. 2. The graph also illustrates the huge volatility of fossil fuel prices observed in the recent past. As the price effect of the 1970s oil shocks disappeared in the early eighties the world experienced a phase of relatively stable prices with growing output until 2003. From 2003 until 2008 prices escalated. After a dip due to the recession in 2009 they increased again.

The future global average oil price starts at 8.1US$/GJ in 2015 (in today's prices 55US$/barrel) and increases to 11.3US$/GJ by 2030 because of a transition towards higher cost oil deposits as cheap oil deposits are limited and decline (see Fig. S6). During this transition phase prices significantly exceed average extraction costs (see Fig. S7). After 2030 oil prices stagnate around 11US$/GJ and increase strongly close to the peak of oil production. The increasing price is not strong enough to avoid peak oil. Despite this marked increase the figures are lower than the oil price assumptions by IEA (2011) that range from 14.3 to 20.6US$/GJ until 2035. Comparing with US EIA (2011) analysis the Baseline scenario lies between the medium (18.1US$/GJ) and the low oil price scenario (7.4US$/GJ).

The global average gas price starts at 4.3US$/GJ in 2015, ranging between 2.5 and 5.9US$/GJ, with exporting (importing) regions at the lower (upper) end. Natural gas prices escalate less than oil prices because gas reserves are still relatively abundant over the next two decades. Import regions are producing also from non-conventional sources like shale gas, since trade costs lead to a relatively high domestic price. The price assumptions of IEA (2011) are considerably higher for the two gas importing regions Europe and Japan, where gas prices increase up to 11.8US$/GJ until 2030 and are nearly twice the US import prices. In the present scenario the global average price of natural gas relative to oil starts at 0.52, decreases to 0.48 around 2030 and stabilized around 0.6 at the end of the century.

The global average price of coal starts at 1.7US$/GJ in 2015, ranging between .8 and 2.0US$/GJ. Low cost coal reserves are still plentiful and, thus, supply grows at moderate prices. Over the longer term, however, the average coal price reaches 7.1US$/GJ. The price ratio of coal to oil starts at 0.21, and increases to nearly 0.3 at the end of the century. In the 1990s the ratio was at 0.6 and decreased to 0.3 in the first decade of the 21st century. IEA (2011) assumes a nearly constant ratio of 0.2 until 2035.

There is a growing literature on fossil fuel price increases, with a particular emphasis on oil prices. Hamilton (2009), Kilian (2009) and Fan and Xu (2011) highlight demand growth. Askari and Krichene (2010) highlight the price-unresponsive supply side since 2010. Besides such fundamental factors other short-term and transitory issues are considered. Askari and Krichene (2010) identify expansionary monetary policy as an important oil demand driver. Kaufman (2011) mentions mutually reinforcing interactions between production declines in non-OPEC countries and changes in futures markets. Dees et al. (2008) and Fan and Xu (2011) also identify speculation as a crucial factor; the former also note bottlenecks in refinery capacities. Market power by OPEC is, however, not identified as an important factor (Dees et al. 2008; Hamilton 2009). REMIND explains energy prices based on market fundamentals and does not consider other transitory effects, though they are important price drivers. The integration of such transitory effects poses a major research challenge.

Fig. 3 shows the net present values of resource rents[2] differentiated by fuel and region. The total fossil resource rent adds up to 29.9tril.US$. The largest rent accrues to oil (18.3tril.US$) from which the MENA region receives the largest share (10.4tril.US$). The global gas rent is 8.2tril.US$ and mainly earned by the MENA region, Russia and the US. The coal rent is the smallest (3.5tril.US$) mainly earned by the US and China. Gas and coal rents are distributed more evenly across regions than the oil rent due to the geographical distribution of endowments and transportation costs. The transportation costs form a barrier protecting domestic producers in import regions with relatively high prices. Exporters can only charge rents net of transportation costs. The effect is more pronounced for gas and coal than for oil. Hence, oil exporters can profit more from the world market price (see Fig. S7).

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[2] Rents are the discounted stream of annual profits of a region from selling fossil resources. For each region we use the domestic price as well as the production costs and the domestic transportation costs. The international transportation costs need not be taken into account because they are equivalent to the price differences to the international market price. See also Fig. S7&8.

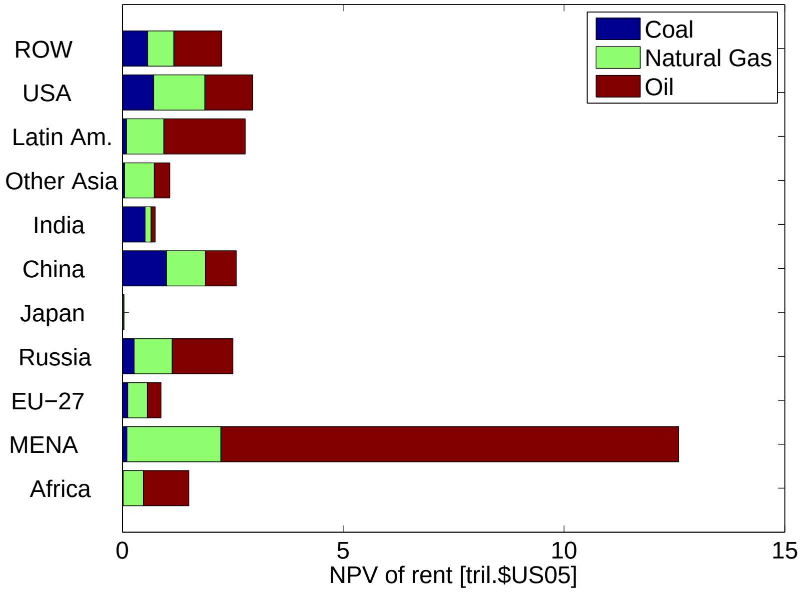

**Fig. 3** Net present value of fossil fuel rents (2010–2100) in the Default baseline. The discount rate is 5 % p.a. ROW indicates ‘Rest of World’ and MENA ‘Middle East, North Africa’

## 3.2 Sensitivity of Baseline Assumptions

Fig. 4 shows the cumulative changes of fossil fuel consumption during the 21st century use for variations of economic growth assumptions and cumulative fossil fuel supply in the baseline scenarios (see Fig. S1&2 and also S9-11). Changes in economic growth assumptions increase fossil fuel demand by 4.9ZJ in the Fast Growth and decrease it by 5.7ZJ in the Slow Growth scenario; $CO_2$ emissions change accordingly. In the High Fossils scenario the consumption of oil and gas increase by 8.7ZJ and 7ZJ, respectively, whereas coal consumption decreases by 4.2ZJ.[3] The inter-fuel substitution effect comes from the smaller deployment of coal-to-liquids and higher gas use in the electricity sector. In the Low Fossils case all fossil fuels decrease significantly by 18.4ZJ and $CO_2$ emissions by 1420Gt.[4] In the case of Low Oil the consumption of coal and gas increase by 7.9ZJ and 10.4ZJ, respectively, but oil output declines by 8.3ZJ. In the High Coal case oil and gas use is reduced by 14ZJ, but the nearly equal increase of coal consumption leads to net positive impacts on $CO_2$ emissions. In the High Gas case total $CO_2$ emissions increase by 300Gt because the boost in natural gas consumption (8.6ZJ) outweighs reductions of coal (1.5ZJ) and oil consumption (0.6ZJ). In summary, the fossil fuel use and CO2 emissions react more sensitive to change in fossil fuel supply than in long-term energy demand.

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[3] This sensitivity is also observed in the GCAM and the WITCH model. Hence, the result is a property of variations in assumptions and not model-specific.

[4] The Weak Policy scenario leads to cumulative emission reductions of only 840GtCO2 mainly due to 6.1ZJ less coal consumption.

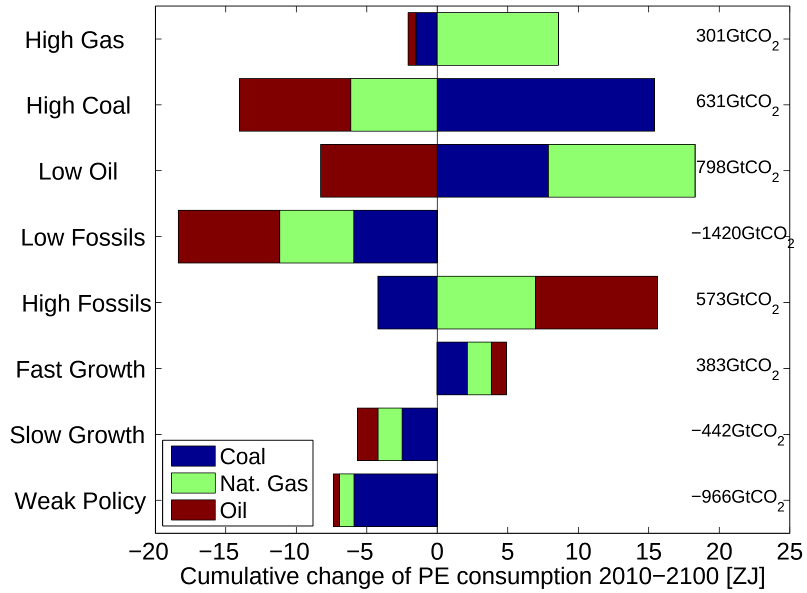

Fig. 4 Differences of global cumulative fossil energy consumption 2010–2100 compared with the Default Baseline. The use of coal, oil and gas is 26ZJ, 23.2ZJ and 25.5ZJ, respectively. The unit ZJ is 1021 Joules. Carbon emissions are 5780GtCO2. The numbers on the right hand part of the graph indicate the change in cumulative CO2 emissions. The unit GtCO2 is 109 metric tons of CO2). The case “Low Oil” indicates low availability oil and high availability of coal and gas; the case “High Coal” is the same but the availability of gas is assumed low; “High Gas” indicates medium availability of oil and coal, but high availability of gas; the case “Weak Policy” considers moderate policies explained in more detail in Luderer et al. (this issue)

Fig. 5 shows the sensitivity of global average oil prices. The oil price depends more on cumulative fossil fuel supply than on energy demand driven by GDP growth. The difference is significant in the near term as changes in fossil supply induce immediate price differences. The short-term oil price grows at a higher rate in the Low Fossils case reaching 13.8US$ per GJ in 2030, whereas it is significantly lower in the High Fossils case. Even in the Low Fossils case the oil price is lower than in the IEA (2011) assumptions, and in the High Fossil scenario it would be less than half.

Low-cost natural gas is relatively more abundant than low-cost oil in all cases, and therefore the initial natural gas prices are less sensitive to resource assumptions (see Fig. S10). In the longer term, fossil fuel supply is more important for natural gas prices than demand growth. The ratio of gas to oil prices over time is nearly the same in all baseline scenarios, except for the High Fossils case in which the ratio is closer to unity. Near-term coal prices are generally the same with one exception: The very pessimistic assumption of low cost coal availability (only 25% of coal reserves are assumed) in the Low Fossil case leads to a 60% increase of the global average coal price.

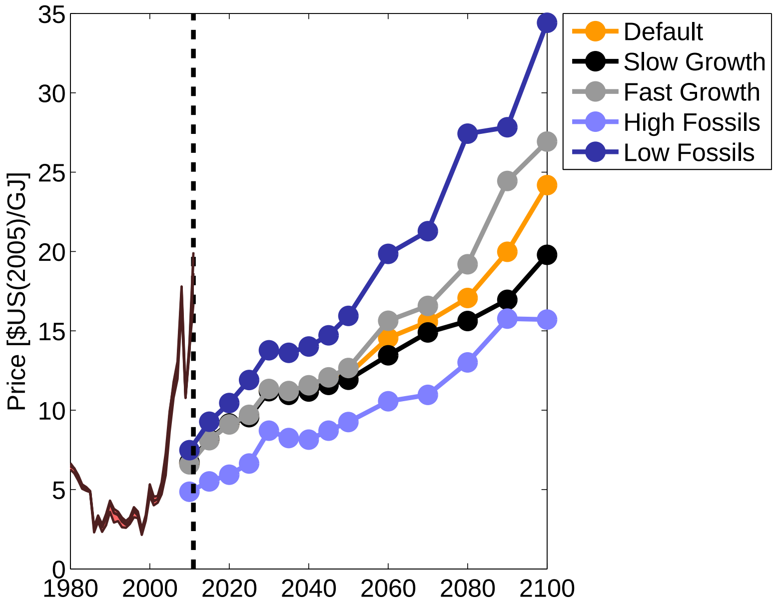

**Fig. 5** Global average oil price for the history (1980–2011) and baseline scenarios (2010–2100). Source of historical prices: BP (2012)

### 3.3 Implications of Mitigation on Fossil Fuel Use and Rents

The imposition of stabilization targets has strong impacts on the fossil energy sector. Fig. 6 compares the use of fossil fuels, the net atmospheric $CO_2$ emissions from energy and industry and the $CO_2$ removal from the atmosphere through bio-energy combined with CCS in stabilization scenarios. There are three noteworthy findings.

First, coal use reacts most sensitively to climate change stabilization and is reduced by 55-85% for the 550-e and 85-90% in the 450-e case. Oil consumption declines much less. The variation of fossil fuel use with baseline assumptions is significantly reduced with climate policy. The more stringent the stabilization target the smaller is the variation. This is due to the constraint on fossil fuel combustion that largely decouples fossil energy use from fossil fuel availability and energy demand. The decoupling is strongest for coal and weakest for oil. Fig: S13 shows the response of fossil fuel prices to the reduced demand in the climate policy scenarios. Near term price reductions are only observed for coal.

Second, the cumulative consumption of oil exceeds the conventional reserve and resource estimates of 11.6ZJ for both climate stabilization targets. For the 550-e case, cumulative consumption also exceeds the additional amount of non-conventional oil reserves (3.4ZJ). In contrast, non-conventional oil resources will be used only in the baseline cases without climate policy. Natural gas consumption in all baseline and 550-e scenarios exceeds the total conventional endowment (16.5ZJ). Coal consumption exceeds reserves in all baseline scenarios, but in stabilization scenarios a significant share of the reserve will be left underground.

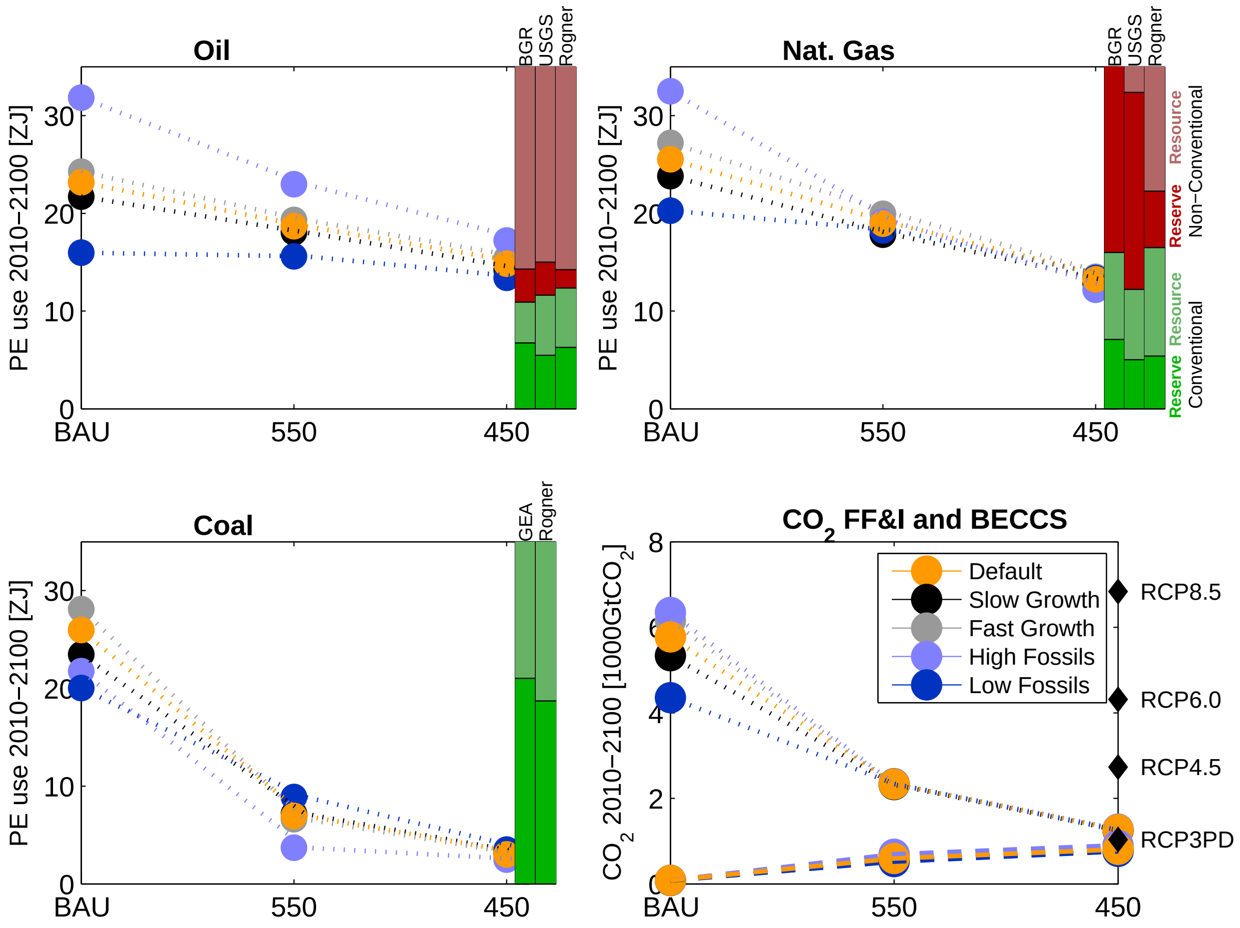

**Fig. 6** Cumulative global fossil fuel use and $CO_2$ emissions 2010–2100 for different scenarios. The lower right graph includes the cumulative net $CO_2$ emissions from fossil fuels and industry FF&I (dotted lines) as well as the CO2 captured and sequestered from bio-energy BECCS (dashed lines). For the purpose of orientation the diamonds on the right hand axis of the bottom-right indicate the cumulative emissions of the representative concentration pathways (data from http://www.iiasa.ac.at/web-apps/tnt/RcpDb). The stacked bar plots to the right hand side of the three fossil fuel plots show estimates of fossil fuel availabilities (Rogner 1997; BGR 2010; GEA is Rogner et al. 2012); USGS is taken from GEA. Note: the extraction sequence suggested by the stacked bars is not necessarily the economically rational sequence; some non-conventional reserves can be cheaper than conventional resources

Finally, cumulative $CO_2$ emissions are approximately 2330Gt$CO_2$ in the 550-e cases and 1260Gt$CO_2$ in the 450-e cases. The diamonds on the right hand axis indicate the corresponding amounts for the representative concentration pathways (RCPs; Van Vuuren et al., 2011) whose climate outcomes have been investigated in the most recent climate model comparison study (CMIP5). It can be seen that the baseline variation of emissions spans the range between the two high RCPs, while the 450 ppm $CO_2$-eq scenario leads to cumulative emissions on the order of RCP2.6. The cumulative amount of bio-energy in combination with CCS is 520-700Gt$CO_2$ in the 550-e cases and 760-900Gt$CO_2$ in the 450-e cases.

Fig. 7 shows that the adoption of the stabilization targets has an unambiguously negative impact on global fossil fuel rents that is overcompensated by the newly generated global rent from carbon emission allowances. The global fossil fuel rent in the baseline case (29.9tril.US$) falls by 8.7tril.US$ for the 550-e target and by 12.4tril.US$ for the 450-e stabilization target.

Reduction of the oil rent is largest (3.5tril.US$), closely followed by coal, if the 550-e target is imposed; for the 450-e target the reduction of the oil rent is 5.7tril.US$ and natural gas rent loss is second with 3.6tril.US$. The carbon rent is 21.2tril.US$ for the 550-e and 31.9tril.US$ for the 450-e case. Carbon prices are shown in Fig. S12. Regional changes of carbon rents are shown in Fig. S14. It shows that regions with high energy demand like China would generate huge carbon rents that are much larger than the loss of fossil fuel rent. For other regions including the Middle East and North Africa showing the largest loss of fossil fuel rent the carbon rent is still sufficient to compensate. However, for a country like Russia the compensation is not feasible based on the domestically generated carbon rent. In summary, the loss of fossil fuel rent could be compensated by the carbon rent at the global level, but this does not hold for necessarily hold for all countries.

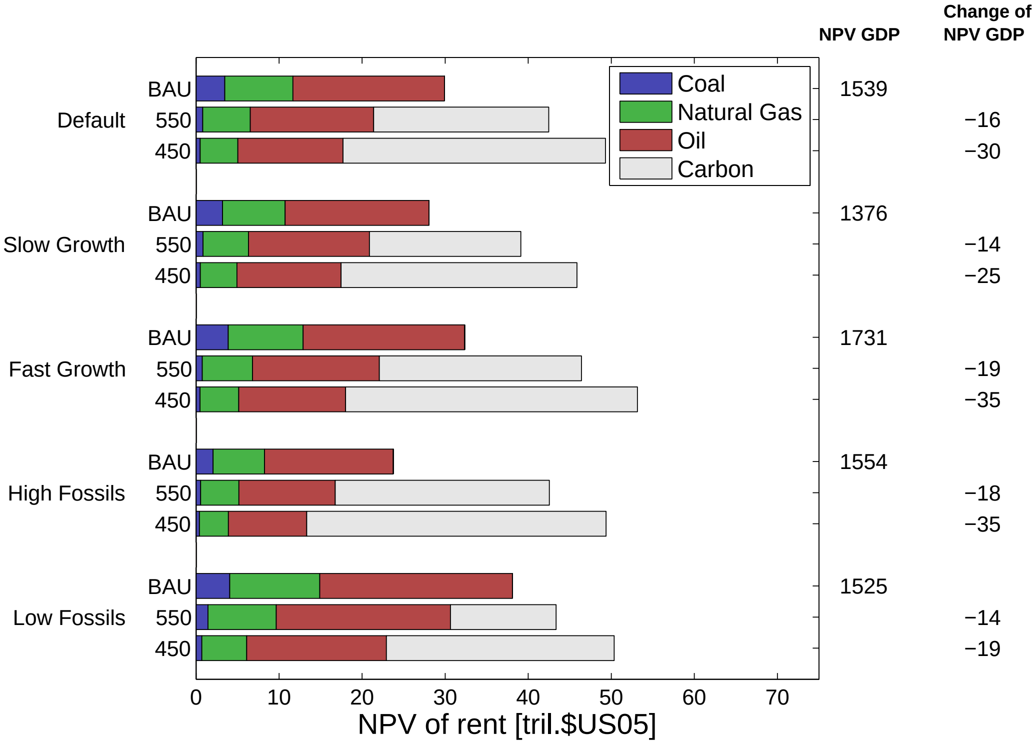

**Fig. 7** Net present value NPV (2010–2100) of global fossil fuel rents and the global carbon permit rent. On the right hand side of the graph we present the NPVof GDP in trillion US$05 and the changes from climate change stabilization policies. The discount rate is 5 %

Fig. 7 puts the climate policy impacts on fossil fuel and carbon rent and net present value GDP into perspective. GDP losses are no longer available to society, with part of the loss borne by fossil fuel owners due to decreased sales (see Fig. S13). In contrast, fossil fuel rent loss associated with lower prices for the residual fossil fuel use is transformed into the carbon rent, which can in turn be redistributed.

The fossil fuel rent increases with energy demand expected pattern, since higher demand increases fossil fuel use and the price (32.4tril.US$ in the high growth scenario *and vice versa*28.1trilUS$ in the slow growth case). The carbon rent also scales with total demand, and overcompensates the losses in fossil fuel rent also under slow and fast GDP growth. The sensitivity with respect to variations of fossil supply combines price and quantity effects that work in opposite directions. In this study the price effect is stronger and, thus, the fossil fuel rent is smaller in the High Fossils case (23.8trilUS$) and higher in the Low Fossils case (38.1tril.US$). The reason is that fossil fuels are limited and difficult to substitute and, hence, the implicit demand curves are price-inelastic. Supply side variations have a larger impact on fossil fuel rents than demand side variations. This continues to hold under climate policy conditions.

# 4. Conclusion

Policies aiming at climate change stabilization will strongly affect fossil fuel markets. The energy market response to climate policy intervention shows several features that are robust to changes in energy demand and fossil fuel supply. The reduction of coal consumption is strongest, and a large part of the reserve would remain unused in the 450-e and 550-e stabilization cases. However, since coal is plentiful and relatively easy to substitute, the coal rent is already small in the absence of climate policy, and therefore its reduction due to climate policy limited. Oil and gas consumption is much less reduced by climate policy. Cumulative oil consumption under strong climate change mitigation is comparable with the amount of conventional oil resources and partly non-conventional oil reserves. Also cumulative gas use exceeds the conventional gas reserve. Despite the continued use of oil in the climate policy scenarios, the loss of oil rents is the largest among the fossil fuels because oil is scarce and difficult to substitute, and climate policy prevents the transition to high cost deposits. Thus, the reduction of the oil rent is mainly due to a decrease in oil prices. The price effect on the oil and gas rent adds to the finding of Grubb (2001), who focused only on the quantity effect.

A key finding of our analysis is that the loss in fossil fuel rents is over-compensated by the carbon rent introduced by climate stabilization targets (see Kalkuhl and Brecha, 2013). It accrues to the owner of the emissions allowances, and therefore opens the possibility to compensate those that lose from climate policy. We also show that this is not necessarily the case at the country level based on the domestically generated carbon rent. Assuming that the efficiency of markets is not affected by the initial allocation of freely tradable emission permit among regions, admittedly a strong assumption, the results demonstrate the availability of permit allocations schemes that would compensate fossil fuel rent losses of all regions. The essential point is that the fossil fuel rent depends on natural endowments whereas its reduction as well as the compensation depends on international climate policies. The carbon rent, however, cannot only be seen as a compensatory fund for the loss of fossil fuel rents because higher final energy prices will also lead to economy-wide losses of GDP. Moreover, the large values of rents and their redistribution must also be treated with care. The rents are subject to various uncertainties and the compensation of their losses with the climate rent discussed here does not suggest that such compensation mechanism is required. The general findings on rent redistribution are robust against variations in energy demand and fossil supply assumptions. For future fossil fuel use and rents, assumptions about fossil fuel supply are more important than the assumptions about future energy demand.

For improved understanding of the interaction of fossil fuels markets and climate policies a number of improvements are desirable. The role of bio-energy with CCS as well as afforestation must be analyzed in more detail, because the capability to produce negative emissions can allow prolonged use of fossil fuels (see Nemet and Brandt 2011). Moreover, the current high fossil energy prices are the subject of heated debates. It is crucial to understand the reasons (including structural under-investment in the extraction sector, strategic behavior, etc.) for the high prices and whether these prices are only transitory or permanent. In case of permanence we need to understand whether this is due to techno-economic costs or geological scarcity or other reasons. If these prices are only transitory it is important to understand the role of dynamic factors of expanding supply and whether climate policies (or efficiency measures) would have a drastic impact on the prices by reducing demand. Finally, climate policies also affect assets (uranium, land, etc.) other than fossil fuels. Hence, a more comprehensive analysis of distributional consequences of climate policies is a promising field of future research.

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