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No. 1926 | May 2014

Web: www.ifw-kiel.de

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Worse off from reduced cost? The role of policy design under uncertain technological advancement*

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Abstract:

A simple model is used to illustrate the effects of a reduction in (marginal) abatement cost in a two country setting. It can be shown that a the country experiencing a cost reduction can actually be worse off. This holds true for a variety of quantity and price based emission policies. The most important channel is that a country with lower abatement costs engages in additional abatement effort for which it is not compensated. Under a quantity based policy with a given allocation, a seller of permits can also be negatively affected from a lower carbon price. We also argue that abatement cost shocks to renewable energy and carbon capture and storage (CCS) are different in terms of their effects on international energy markets. A shock to renewable energy reduces fossil fuel rents benefiting energy importers, while the opposite holds for a shock to CCS. The channels obtained in the theoretical model can be confirmed in a more complex global computable general equilibrium model. Some regions are indeed worse off from shock that lowers their abatement costs.

Keywords: Climate policy, prices vs. quantities, renewable energy, CCS, technological uncertainty, CGE model

JEL classification: C68, Q54, Q58

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*Acknowledgements:
I am deeply indebted to Sonja Peterson for very helpful comments. I would like to thank Michael Rose for his valuable research assistance. Funding by the German Federal Ministry of Education and Research (reference 01LA1127C) is acknowledged.

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1 Introduction

In order to avoid dangerous climate change, deep and costly cuts in CO_2 emissions on a global scale are unavoidable. Cost for emission reductions are determined by the underlying demand factors such as population and economic growth and supply factors such as efficiency improvements (IPCC, 2007). Since these underlying factors are not deterministic, therefore also the resulting emissions or costs of emission abatement are uncertain. An unanticipated shock to these demand or supply factors can move abatement costs away from their expected value.

It is obvious that macroeconomic shocks affect the cost of reducing emissions to a given level. A lower growth rate leads to less aggregate demand for fossil fuels and thus less abatement effort to reach a certain emission level. The recent financial crisis can serve of an example of how an economic slowdown can also lead to a drop in CO_2 emissions. In Europe, part of the decline in prices for CO_2 can be explained by lower demand for fossil fuel (Ellerman et al., 2014). On the other hand, more rapid economic growth can accelerate emissions. Following China's entry into the WTO and the subsequent export driven growth, emissions in China exceeded projections (Blanford et al., 2009).

Another source for uncertainty of abatement costs lies in the uncertainty of technological advancement and thus the cost development of low carbon energy sources. The availability of cheap renewable energy options or carbon capture and storage (CCS) makes abatement more affordable. Many of the cost estimates and scenarios for possible future energy systems rely on assumptions of technological development in key technologies, which today still play only a minor role or are at their infancy. But it is uncertain whether these technologies can live up to the expectations placed on them. Most prominently, various renewable energy technologies and CCS play a crucial role in many future low carbon scenarios. In general, economic costs estimates of future emission reductions are quite sensitive to changes in the underlying assumptions on inclusion of key technologies like CCS or renewables, especially for scenarios aiming at very low emission levels. For example, economic costs for mitigation can be substantially higher when CCS is limited or not available (Edenhofer et al., 2010; Luderer et al., 2012; Kriegler et al., 2014). The (policy driven) fast expansion of renewables in Europe has also demonstrated that the availability of renewable energy can lead to lower carbon prices. The result from this overlapping regulation is a decline in emission prices and a thus a reduction in the cost of emission abatement within the emission trading scheme (ETS) (Böhringer et al., 2009).[1] In this paper we focus on the effects of shocks to cost of key abatement technologies, more specifically their future cost.

These examples of shocks obviously have a strong direct impact on the country where they originate, yet in today's interconnected world shocks will also affect other countries indirectly.[2] One important transmission channel is changes in international energy prices. A lower demand for energy in response to a shock would lead to lower energy prices and thus affect exporters and importers of fossil fuels. With respect to this transmission channel, shocks to renewable energy and CCS are likely to be different because a positive shock to renewable energy will lower the demand for fossil fuel while this is not necessary the case for CCS (Kalkuhl et al., 2014). Important questions related to the nature of shocks therefore are: How do different types of technology shocks affects other countries? What are the different channels for transmission? What is the role of positive correlation between shocks in different countries?

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[1] The total welfare cost increases because renewable energy requirements constitute an additional constraint in the cost minimizing problem; however the emission reduction within the ETS only is reduced.

[2] Shocks to cost of key abatement technologies are likely to be positively correlated so that all countries will enjoy a cost reduction. However, the benefit will be higher in countries that can make better use of the technology, e.g. because of geographical features.

The different transmission mechanisms can be influenced by the instrument choice to regulate emissions. McKibbin et al. (2008) have demonstrated that unexpected macroeconomic shocks in one country always have some, yet different, feedback effects on other countries under a price based and a quantity based emission control policy, respectively. While a carbon tax as an instrument has no repercussion on interlinked emission trading schemes, effects on other markets such as international fossil fuel markets might be more pronounced compared to an ETS system. These feedback effects on the fossil fuel market are acknowledged in the literature (Böhringer and Rutherford, 2002; Klepper and Peterson, 2006), yet have not explicitly been analyzed with respect to the choice of policy instrument under (technological) uncertainty.

While it seems to be straightforward that countries would benefit from reduced abatement costs caused by lower costs for the deployment of renewable energy or CCS technologies, this might in fact depend on the policy instrument. It is even possible that under certain circumstances lower abatement cost can lead to higher total cost. Under a price based system with a fixed carbon price, lower than expected abatement cost would translate into additional (costly) abatement effort. A negative effect could also happen under an emission trading scheme. Suppose that in an emission trading scheme a country is a net seller of permits. Then lower marginal abatement costs reduce the carbon price and hence the value of the permits it can sell – the overall effect of a seemingly positive shock could well turn out to be negative. Questions in the realm of policy design can thus be formulated as follows: How can the choice of policy instruments influence international transmission of a technology shock? Can policy design lead to additional cost as a result to lower abatement costs? How should this be taken into account when designing policies?

These considerations are further developed with a simple theoretical model in Section 2. To better understand whether these results also apply in a more realistic setting, a computable general equilibrium (CGE) model is used to assess the impacts of a technology shock under different policy instruments in Section 3. This allows to tackle questions like: Do these theoretical arguments also carry over to a more complex model? What is the relative importance of the different channels? Section 4 finally discusses implications and concludes.

2 Simple theoretical model

2.1 Repercussions under different policy instruments

In this section, a simple two country model is used to illustrate the effects of different policy instruments on the distribution of abatement costs. For simplicity, quadratic marginal abatement costs (MAC) are assumed, as there is some evidence for this form (Klepper and Peterson, 2006; Klepper, 2011). Marginal abatement costs in countries $i = 1,2$ depend on the level of abatement a_i. Without loss of generality, they can be described

$$MAC_1(\phi, a_1) = \frac{\beta}{\phi} a_1^2; \;\; \phi, \beta, a_1 > 0 \tag{1}$$

and

$$MAC_2(a_2) = a_2^2; \;\; a_2 > 0 \tag{2}$$

where β represents a parameter in order to allow for different MACs in different countries and ϕ is a parameter representing a technology shock. ϕ is anticipated to be equal to one and an unexpected technology shock $\phi > 1$ shifts the MAC_1 downward.[3] The efficient level of abatement to achieve a

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[3] In this section we only analyze the impacts of a shock that leads to lower abatement costs in an abatement technology.

given abatement target[4] $\bar{a}$ can be found by minimizing total abatement costs

$$\mathscr{L} = \int_0^{a_1} MAC_1(\phi, x_1)dx_1 + \int_0^{a_2} MAC_2(x_2)dx_2 + \lambda\left(\bar{a} - \sum_i a_i\right). \tag{3}$$

The first order conditions show that the efficient solution is characterized by equalization of marginal abatement cost at λ

$$\lambda = \frac{\beta}{\phi}a_1^2 = a_2^2. \tag{4}$$

The individual quantities of abatement consequently depend on the technology parameters β and ϕ, such that the country with cheaper abatement options carries out more abatement

$$a_2 = \sqrt{\frac{\beta}{\phi}}a_1. \tag{5}$$

When emissions are controlled by either a tax or an emission trading scheme, in expectations (i.e. when $\phi = 1$) a price based instrument and a quantity based instrument are equivalent. In both cases, emissions are reduced when the MAC is below the price of a carbon tax or carbon permits, respectively.

2.1.1 Tax

Under a tax scenario, the carbon price is held constant at $\bar{\lambda}$ regardless of any deviation from $\phi = 1$. Abatement is carried out as long as the marginal abatement costs are below the tax rate. Tax revenues are assumed to be returned lump sum and are thus discarded from the analysis. When there is a shock to marginal abatement costs (i.e. ϕ increases), cost for each unit of abatement is lowered. At the same time, however, the amount of abatement is increased because now a larger quantity of abatement can be curried for a cost below $\bar{\lambda}$. Taking the integral of marginal abatement costs from equation (1) yields total abatement cost C for the quadratic case, which depend on the technology shock and the level of abatement

$$C_1 = \frac{1}{3}\frac{\beta}{\phi}a_1^3 \tag{6}$$

The level of abatement a_1 will adjust such that the new marginal cost is equal to the (unchanged) tax rate. From equation (4), it can be calculated as

$$a_1 = \sqrt{\bar{\lambda}\frac{\phi}{\beta}} \tag{7}$$

When there is a shock to abatement costs (i.e. $\phi > 1$), abatement and abatement costs for country 2 are not affected by the shock. The cost for country 1 is influenced by two opposing factors

$$\frac{\partial C_1}{\partial \phi} = \underbrace{-\frac{1}{3}\frac{\beta}{\phi^2}a_1^3}_{<0} + \underbrace{\frac{1}{3}\frac{\beta}{\phi}\frac{\partial a_1^3}{\partial \phi}}_{>0} \tag{8}$$

The first term reflects lower cost from abatement that would have been carried out also in the absense of a shock, the second term reflects changes in the quantity of abatement which is adjusted

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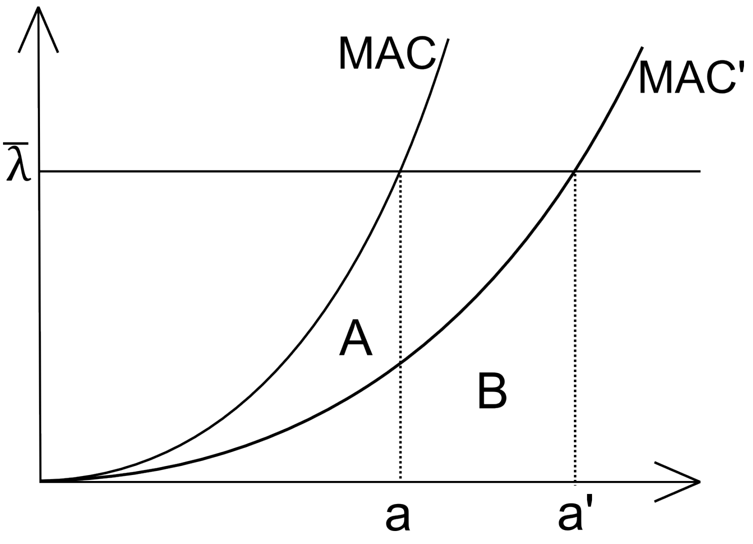
The results however can easily be carried over to the case when costs of abatement technologies are higher than expected.

[4] Note that this model does not explicitly include marginal damages and we assume here an exogenous target for emissions. A comparison of marginal damages and marginal abatement cost would however be required to find the optimal policy instrument under uncertainty (Weitzman, 1974). The aim of the paper is not to determine an optimal policy, but rather to stress the characteristics of policy instruments under abatement cost uncertainty.

Figure 1: Change in abatement cost due to a technology shock under an emission tax policy.



according to equation (7). As there is one positive and one negative term, a technology shock can thus lead to cases where a country which experiences a shock to lower MACs has to bear higher abatement costs. For the case of quadratic marginal abatement cost curves a technology shock always increase total abatement costs.[5] Figure 1 shows the opposing effects of equation (8) graphically. The area under the MAC curve represent abatement costs. The technology shock shifts the MAC downward to MAC'. Total cost is reduced by *A*, yet additional abatement leads to an increase of cost by *B*.

Note that the additional cost from additional abatement might bring along some gain due to avoided damage. Here we focus however on the distributional effects and show that a technology shock under a tax regime can increase the cost of the country which experiences this shock.[6]

2.1.2 Permits with auction

When ex ante not the price but the overall level of emissions is fixed there are different forms of distributing emission rights. When emission rights are auctioned, there is no trade in permits (i.e. no implicit transfers). However, compared to the tax, there is certainty about the quantity of abatement. Similar to the case of taxes, it is assumed that auction revenues are recycled lump sum to the country which is buying the permits. Because the amount of global emission permits is fixed, their price can react to the shock. This affects the choice of optimal emission levels both in the country directly affected by the shock and the other country influenced only indirectly through reactions in the carbon price.

Rather than assuming a fixed level of emissions, it is more straightforward to follow the model from above and keep the model in units of abatement. Plugging in (4) into the cost expression from (6), cost can be expressed as $1/3\lambda a_i$. Total cost depends on the carbon price and the quantity of abatement. Note, however, that in contrast to the case above, λ is not fixed but reacts to a technology shock. Differentiating cost with respect to ϕ, there are again two oposing effects for country 1.

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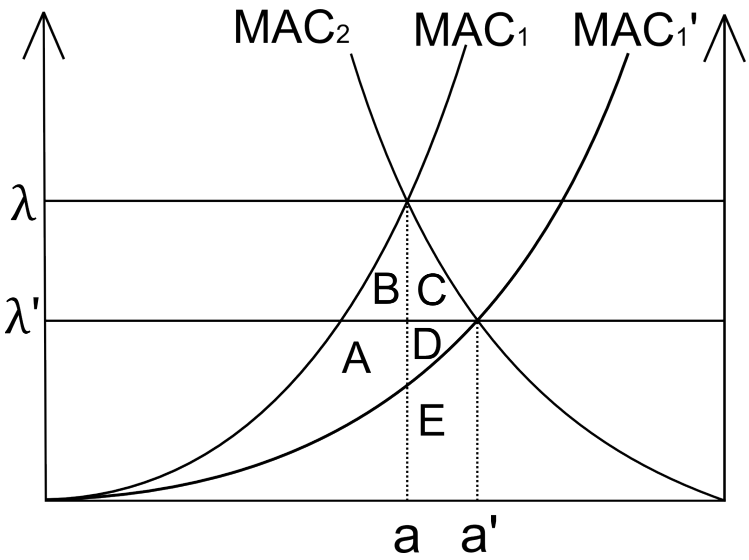
[5] Plugging the expression for a_1 from equation (7) into (6) and differentiating with respect to ϕ yields $\frac{1}{6}\frac{\bar{\lambda}^{\frac{3}{2}}}{\sqrt{\beta\phi}}$ which is larger than zero, indicating rising costs for the quadratic case. For other convex functions it is a priori not clear which of the two effect dominates. For a function which is relatively flat at first and then quickly turns steeper area *A* might exceed area *B* in Figure 1.

[6] This result is comparable to Peterson and Klepper (2007), who state that under a globally harmonized carbon tax countries with lower marginal abatement costs will face higher total abatement costs.

Figure 2: Change in abatement cost due to a technology shock under an quantity policy with a global auction.



$$\frac{\partial C_1}{\partial \phi} = \underbrace{\frac{1}{3}\frac{\partial \lambda}{\partial \phi} a_1}_{<0} + \underbrace{\frac{1}{3}\lambda \frac{\partial a_1}{\partial \phi}}_{>0} \tag{9}$$

The two oposing terms and their interpretation is similar to that of the terms in equation (8). The first term is negative because the same overall abatement $\bar{a}$ can now be carried out at a lower cost. The sign of the second term follows from equation (5) and the fact that total abatement is unchanged. A higher ϕ leads to more abatement from country 1 and less abatement from country 2. It is therefore not clear how the total cost of country 1 reacts and it again is possible that lower abatement cost due to a technological change lead to higher total abatement cost. Cost of country 2 on the other hand will decline unambiguously

$$\frac{\partial C_2}{\partial \phi} = \underbrace{\frac{1}{3}\frac{\partial \lambda}{\partial \phi} a_2}_{<0} + \underbrace{\frac{1}{3}\lambda \frac{\partial a_2}{\partial \phi}}_{<0} \tag{10}$$

Figure 2 shows this graphically. The length of the abscissa corresponds to the total abatement requirement $\bar{a}$. The MAC for country 1 is shown from left to right, while the MAC from country 2 is shown from right to left. The equilibrium would be at carbon price λ and the abatement set a with a_1 and a_2. A shift to MAC' changes both the carbon price (to λ') and the abatement set (to a'). Country 1 enjoys lower abtement cost A and B, but additional abatement cost E. Country 2 can reduce its abatement and thus abatement cost by C, D, and E. Country 1 can still experience a loss (when E exceeds A and B), however, this is smaller than the loss under the tax case. This is because the level of total abatement remains unchanged after a shock.

Under an auction setting, total abatement cost declines by A, B, C, and D, but it depends on the relative slope of MAC_1 and MAC_2 how the gain is shared between countries 1 and 2. When MAC_2 is steep compared to MAC_1, a' is relatively close to a and the additional abatement by country 1 relatively small.

2.1.3 Permits with given allocation

The allocation scheme of emission rights in possible future global emission trading system is often proposed to incorporate various equity principles (den Elzen and Lucas, 2005). For example in the largest existing emission trading scheme of the European Union (EU ETS), emission allowances are in part distributed to countries based on these principles. While most allowances are distributed to member states based on past emission levels, 10% of allowances are based on per capita income and benefit poorer member states (EU, 2009, Article 17). These countries can thus benefit from selling the emission allowances on the European carbon market.

In the theoretical model, costs for country i under an emission trading system with some allocation rule can be written as

$$C_i = \frac{1}{3}\lambda a_i + \lambda\left(\hat{a}_i - a_i\right). \tag{11}$$

$\hat{a}_i$ is the amount of permits allocated to country i (and $\sum_i \hat{a}_i = \bar{a}$), the difference between allocated and actual abatement has to be bought or sold at the market price λ. Differentiating with respect to ϕ, we find that a shock influences costs via several channels:

$$\frac{\partial C_i}{\partial \phi} = \frac{1}{3}\frac{\partial \lambda}{\partial \phi} a_i + \frac{1}{3}\lambda\frac{\partial a_i}{\partial \phi} + \frac{\partial \lambda}{\partial \phi}\left(\hat{a}_i - a_i\right) + \lambda\frac{\partial a_i}{\partial \phi} \tag{12}$$

The first two terms are identical to the case where permits are auctioned and refer to actual abatement cost. The last two terms are new and stem from effects from emission trading. The third term describes the change in the value of transfers due to a change in the carbon price. As the price declines, a permit buyer benefits from this effect while a permit seller now sells its surplus permits at a lower price. The last effect finally describes the changes in the trading positions. As there is a shift in relative abatement, country 1 can benefit from generating new abatement to reduce the need to buy permits when it is a permit buyer or to generate additional permits when it is a permit seller.[7]

Compared to the auction case, it is less likely that country 1 is worse off due to the shock because it can benefit from the additional low cost abatement potential by either decreasing the amount of permits it needs to buy when it is a buyer of permits[8] or it can sell additional permits when it is a seller of permits. However, in the later case, there is the possibility that this gain is outweighed by the loss from a lower carbon price at which it can sell permits.

This is illustrated by Figure 3. The figure is similar to Figure 2, but in addition $\hat{a}$ shows the set of abatement allocation. In the figure, the allocation set $\hat{a}$ is chosen such that country 1 is a seller of permits. In the situation without a shock and the abatement combination a, country 1 would sell $a_1 - \hat{a}_1$ permits as it does more abatement than it would be required to. The permits are sold at λ. Since abatement costs are lower or equal to λ it gains $F + G$ from this trade. With a technology shock, the equilibrium shifts to λ' and a'. Abatement costs are reduced by A, B, and H and increased by E as in the case with auctioned permits. As country 1 can now only ask for λ', the gains from carbon trade are reduced by B and F due to the lower carbon price and are increased by A and D. The net gain for country 1 is thus $H + A + D - F$. If the price drop is large and country 1 is a seller of many permits, then it can loose from the technology shock. For country 2, the gains are B and F due to the lower carbon price and C due to a shift in abatement.[9]

Compared to the auctioning scheme, gains are larger for the country 1, because it can use the increase in low cost abatement potential by selling emission allowances to the other country. The

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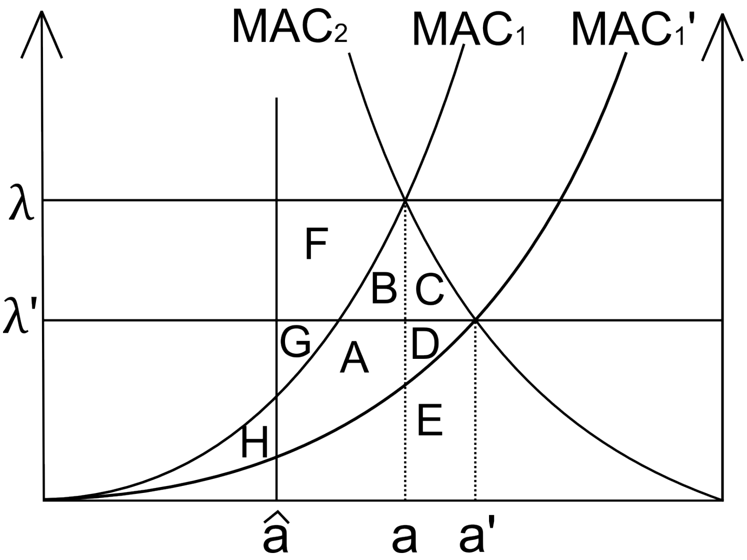
[7] There are of also cases where country 1 could switch from a buyer to a seller. This is not visible in equation (12) as this is only the marginal effect, but could be easily shown in a variation for Figure 3.

[8] In this case it will gain unambiguously because also the cost for the remaining permits it needs to buy declines.

[9] For the interval between a_2 and a'_2 country 2 now prefers to buy additional permits, which is cheaper than own abatement.

Figure 3: Change in abatement cost due to a technology shock under an quantity policy with a given allocation.



other country also gains from this trade because it now pays a permit price that is lower than its own abatement costs – gains for country 2 are however smaller than in the case of an auction. Yet, it is not automatic that a lower abatement cost will lead to lower abatement costs for both countries, because of repercussions in the existing price for carbon and its impact to the value of emission trading.

2.1.4 Correlated shocks

Key abatement technologies are expected to be used in many regions. A shock to a the cost of these technologies can therefore be expected to affect not only one country, but both countries. This leads to shocks which are positively correlated across countries but have varying impacts in the different countries.

In the case of taxes, abatement costs for a given country only depend on the impact of the shock on own cost and on the quantity of own abatement (see equation (8)). There are no spillovers from the policy instrument. With correlated shocks both countries benefit from lower cost for abatement that they would have carried out even without the shock but both countries also engage in costly additional abatement effort. Overall effects should be stronger in the country affected stronger by the shock.

For quantiy based policies however, the optimal abatement level in both regions adjusts to a shock. Let us first think of two extreme cases. When country 2 is not affected at all, the results from above hold. When country 2 is affected equally strong from the shock as country 1, both MACs would shift downward by the same amount. There is hence no shift in abatement, i.e. $\partial a_i/\partial\phi = 0$ and hence there would be no additional cost (in equations (9) and (10) the second term would vanish). Both countries would gain from lower cost to reach abatement levels a_i. Compared to a situation with only one country being subject to a shock, the downward shift in λ would be increased when the shock affects both countries. This means that in the case with fixed allocation the adverse effect for permit sellers is increased.

When the shock affects country 2 not as much as country 1, all channels found in the theoretical model would still be present but weaker than when the shock only affects country 1. The only effect that would be reinforced is the change in value of emission trading (the third term in equation (12)).

To summarize, the theoretical model shows that is possible under all policy settings that a country loses from lower MAC. This is because a shock not only leads to lower cost for existing abatement but also leads to additional abatement. The likelihood for or the extend of a loss depends on how policies adjust the burden sharing in response to a shock. Under a tax system, there is no adjustment and costly additional abatement is not compensated for. Under quantity based policies, the quantity of additional abatement is limited and thus additional cost is lower than under a tax policy. When emission permits are not auctioned but allocated, the adverse effects are further reduced because additional abatement effort generates emission permits and thus a compensation. Under a system with emission trading this leads to lower carbon prices and sellers of emission permits are affected negatively as prices for permits fall due to a shock.

2.2 Repercussions on international fossil fuel price markets

Marginal abatement costs not only depend on the direct emission reductions but are also determined by other factors. One important determinant is the demand for and trade in fossil fuels (Peterson and Klepper, 2007; Morris et al., 2012). Price changes on international fossil fuel markets can significantly impact welfare in fossil fuel importing and exporting countries (Böhringer and Rutherford, 2002). The rents that fossil fuel exporters gain from importers are affected by the price and CGE analysis has shown that MAC shift upwards or downwards when other countries engage in abatement activities (Peterson and Klepper, 2007; Morris et al., 2012).

Shocks to abatement options have the potential to affect demand for fossil energy and thus the rents that resource owners can receive. However, the mechanism of a shock's influence of resource rent can be different under the type of shock and the policy instrument in place. The nature of renewable energy and CCS as abatement technologies is very different in its impact on resource rents (Kalkuhl et al., 2014). Whereas renewable energy can serve as a substitute to fossil fuels and thus reduce the scarcity rents, CCS can make fossil fuel more valuable in a setting of restrictive climate policy because fossil fuels can still be used. In general, a shock to CCS can be expected to benefit for resource owners, while the opposite holds for a shock to renewable energy.

How a shock to different abatement technologies impacts fossil fuel importers and exporters also depends on the policy instrument in place. In an emission trading system, the emission quantity is fixed and as there is a close relationship between carbon emissions and fossil fuel use. A binding emission constraint should therefore not change the quantity of fossil fuel used in the economy.[10] A shock to CCS technology however changes this fixed relationship between fossil fuel use and emissions: For the same amount of emissions a higher amount of energy from fossil fuels can be used, leading to a gain for the owners of the resource. When an easier substitution towards renewable energy is possible due to a shock to renewable energy, however, the demand for and thus the resource rent of fossil fuel declines. This can even be the case under a fixed emission cap and a fixed amount of fossil fuel that can be used because the value of the fuel and thus the rent that the resource owner can extract is reduced.

Under a tax system, the quantity of abatement is endogenous and increases in response to the shock. A shock to renewable energy leads to a lower demand in fossil fuels as they can be better used as a substitute for fossil fuels. In addition to this effect which is similar to the situation under a quantity based system, total abatement will increase (see Section 2.1.1) and thus reduce also the quantity of fossil fuels. A shock towards lower cost for CCS has an ambiguous effect. On the one hand, fossil fuel now has a higher value because it can be better used (as in the case of a quantity

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[10] As different fossil fuels have different emission factors, this is not a fixed relationship. For this part, we assume only one fossil fuel which has a fixed proportion to emissions.

Table 1: Impacts on rents and (global) quantities of fossil fuels as response to shock in abatement costs to renewables and CCS

Policy instrument	Impacts on	Lower abatement costs in:	
		Renewables	CCS
Quantity based	Rent per unit of fossil fuel	Decrease	Increase
	Quantity of fossil fuel	Unchanged	Increase
Price based	Rent per unit of fossil fuel	Decrease	Ambiguous
	Quantity of fossil fuel	Decrease	Ambiguous

based instrument), but on the other hand, the overall level of abatement is higher and lower emissions could mean a lower quantity of fossil fuels that is used. As these effects are influencing demand in opposing directions, a numerical simulation can provide an indication about the relative size of the effects.

Table 1 summarizes the impacts of the different shocks to rents from fossil fuels and to quantity demanded globally under different policy instruments. To summarize, a shock towards lower cost of CCS seems better for resource owners compared to a shock in renewable energy costs. Resource owners are also better off in a quantity based system compared to a price based system.

3 Simulation Results

To illustrate the results from the theoretical model, we use the CGE model DART to run climate policy scenarios with shocks to the cost of abatement technologies. The CGE model captures repercussions both on energy and emission trading markets and can thus provide guidance on the question whether the adverse effects derived in the theoretical model also hold in a more complex setting. The model can also give an indication on the relative importance of transmission channels.

3.1 Model and Scenarios

The DART model is a multi-sector, multi-regional recursive dynamic computable equilibrium (CGE) model (Klepper et al., 2003; Weitzel et al., 2012). It is calibrated to the GTAP 8 dataset (Narayanan et al., 2012) and aggregated to 12 sectors and 13 regions (see appendix). In each region, a representative agent maximizes utility from consumption. Consumption preferences are modeled as linear expenditure system (LES). Income of the representative agent is derived from factor income from labor, capital and land as well as income from tax revenues. The model horizon is 2050.

The model was extended to include different electricity generation technologies which are assumed to be perfect substitutes (Weitzel, 2010). Renewable electricity and CCS in the electricity sector are modeled based on cost data from the TIMER model (de Vries et al., 2001) and recent literature surveys for solar energy (Renz, 2012) and CCS (Lämmle, 2012). These generation technologies require a technology specific factor as input, its fixed supply for a given year leads to an upward sloping supply curve. Costs for these technologies are reduced over the simulation period through learning-by-doing. This is implemented in DART by using different vintages of capital, learning only applies to new capital vintages, to correctly model investment decisions based on the current productivity in a given technology.

As long as costs for renewable electricity exceed costs of conventional electricity generation, subsidies are paid to producers. Subsidies are determined endogenously in the model to achieve at least the deployment level of the current policy scenario in the World Energy Outlook (International

Energy Agency, 2013). This ensures also some learning in the baseline scenario as the level of renewable energy is increasing.[11]

The different technology shocks for renewable electricity and CCS are modeled as follows: For renewable energy, current costs are relatively certain, yet the cost development in the future is uncertain. The technology shock is therefore modeled as a deviation from the expected learning rate, i.e. the rate at which costs are reduced when output doubles. Per design, this effect becomes more visible in the long run. Higher learning reduces the cost of deployment and thus eases switching to low carbon generation technologies. For CCS, the main source of cost uncertainty is not the change of costs, but the general markup of commercially viable CCS compared to the respective conventional generation technologies. The technology shock therefore is modeled as a lower than expected markup.

For the shock in renewable energy, only the learning rates for solar and wind are adjusted, as the largest growth is expected in these technologies in climate policy scenarios (International Energy Agency, 2013). In the shock scenario, the learning rate for wind increases from 15% without a shock to 18.7% and the rate for solar increases from 19% to 22.8%. This is the about the 99% percentile value obtained from a literature review (Renz, 2012). For CCS, the cost markups differ for the model regions and are obtained from a Monte Carlo analysis based on several technological and economic aspects (Lämmle, 2012). For CCS, in the shock scenario we apply the 99th percentile of the probabilistic markup, the average of markup is reduced from 1.74 to 1.51 for coal and from 1.42 to 1.31 for gas in the shock scenarios.[12]

As there is a global market for these technologies, it is likely that lower costs can be applied in all regions. We therefore model shocks affecting all regions, yet the shocks have still different impacts in different regions. This is due to the fact that countries are not equally well suited for the technologies.[13]

The scenarios run here are designed to illustrate the theoretical model. We here analyze a time horizon until 2050 because the abatement technologies under scrutiny will only become relevant when there are sufficiently high carbon prices and learning does not matter much in short run.

The climate policy scenario follows an emission path leading to radiative forcing of 2.9 W/m^2 and a 50% probability to limit climate change to 2 degrees (Johansson et al., 2014) when abatement costs are at their expected level. Without a technology shock, a tax is equivalent to an emission trading system (without transfers).

In line with the theoretical model presented, scenarios are designed here that vary along two dimensions. This first dimension is the nature of shocks (renewable energy or CCS), the second dimension is the policy instrument regulating CO_2 emissions. There are several different options:

- Auction (quantity based system with fixed allowances on a global level): Permits are auctioned yearly and revenues are recycled lump sum to the region that used the permit. There is no emission trading.

- Quantity based emission trading system with fixed national allocations: The emission rights are distributed to and subsequently auctioned by the individual regions. There are two sub-scenarios: In the first sub-scenario, emission allocation to regions is such that in expectation (i.e. when $\phi = 1$) there are no transfers (ntr) through emission trading, i.e. without a shock each region receives as much permits as it has emissions. Under a technology shock, however,

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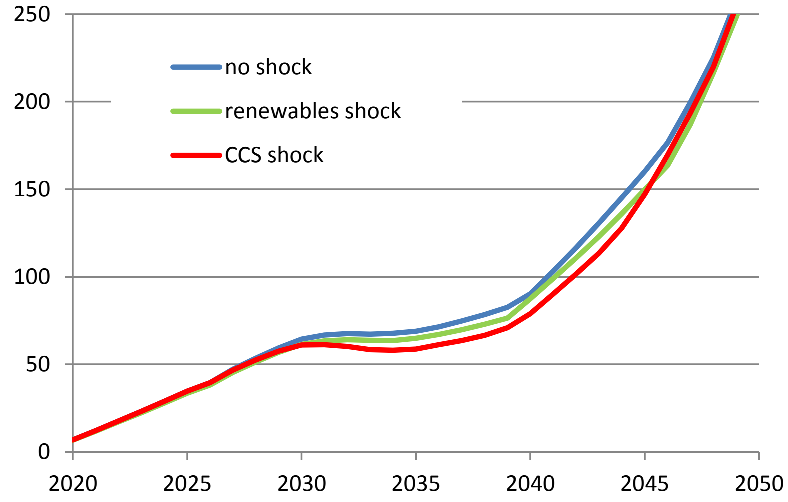
[11] The scenario is not designed to find an optimal policy to exploit learning-by-doing. We are rather interested in the changes of cost induced by a certain shock.

[12] The markups here are simple unweighted averages of the model regions.

[13] The conditions of using a renewable resource are clearly different in different countries. For example, lower cost of solar energy has much less value for Russia than to the Middle East region.

Figure 4: Global marginal abatement cost under different shocks in the "ntr" scenario.



countries affected by the shock and carry out more abatement can sell emission permits on an international carbon market. In terms of Figure 3, this means that $\hat{a} = a$. A second sub-scenario explicitly includes a combination of various equity principles incorporated in the allocation of emission rights. We here use the "Common but Differentiated Convergence" (CDC) regime which prescribes industrialized countries to start with convergence of per-capita emissions in 2020 while developing countries start to converge later (Höhne et al., 2006, see Johansson et al. 2014 for detailed assumptions). This yields an allocation which leads to transfer payments to compensate poor countries with low per capita emission levels. In terms of Figure 3, this means that $\hat{a} \neq a$.

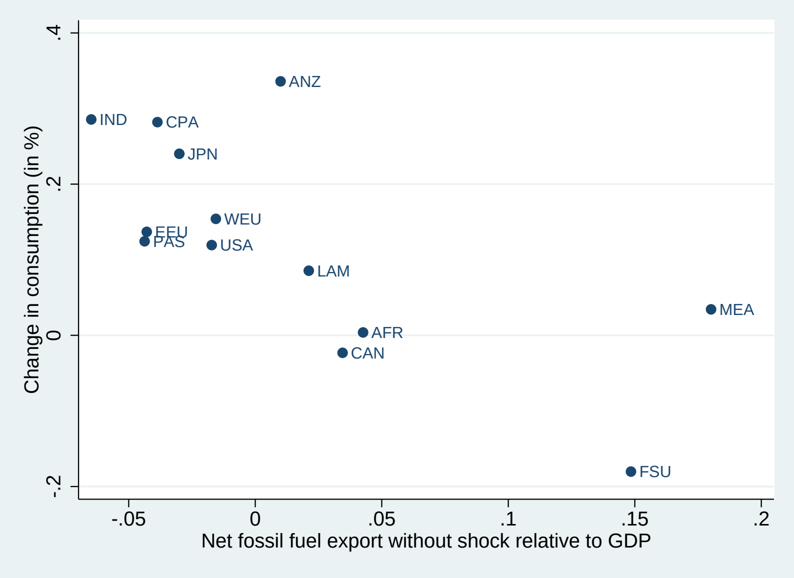
- Price based, globally harmonized tax: Instead of emissions, the carbon price is held constant. The carbon price is determined such that without a technology shock emissions are the same as in "ntr". Under a technology shock, the price is unchanged, but the level of abatement adjusts.

Note that "ntr", "auction" and "tax" yield the same results when there is no unexpected shock. All quantity based scenarios ("ntr", "CDC" and "auction") lead to the same global emissions with and without technology shocks. In the tax case the carbon price is the same both with and without a shock but the level of emissions can adjust. In order to illustrate the role of shocks under different policies, each of the two shock types (renewables and CCS) is combined with each policy instrument in one scenario.

3.2 Findings

Comparing the global marginal abatement costs with and without shocks, it appears that the largest differences occur between 2030 and 2040 (Figure 4). This is the result of two factors. First, as explained above, the shocks as implemented in the model are less important for the short run development, hence there is less variation before these years as less costly abatement options are used (e.g. energy efficiency or fuel switch). Second, the electricity sector still offers potential for decarbonization in this period and marginal abatement costs are in a range where cost differences of renewable energy or CCS can play a role. After 2040–2045, abatement becomes increasingly costly and there is little potential left for renewables or CCS (see also Johansson et al., 2014). For this

Figure 5: Relation of changes in consumption due to a technology shock in renewable energy and net energy trade (under no shock situation, relative to GDP) under a price based policy.



reason, results are presented first by showing simple scatterplots for the year 2035 to understand the general relationship between fossil fuel trade and the impact of a technology shock. Furthermore, simple regressions are used to show the differences between policies, as this allows taking into account several observation years and adding more factors compared to only one factor in the scatterplots. We here use changes in the level of consumption as dependent variable.[14]

As discussed in Section 2.2, it can be expected that the different types of shocks affect fossil fuel markets differently. For the shock in renewable energy sources, substitution away from fossil fuels becomes more affordable and demand for fossil fuel declines which results in lower world market prices. This benefits (net) importers of fossil fuels. This can best be observed under a tax instrument where the reaction on the world market can expected to be largest. Figure 5 clearly shows the changes in consumption[15] are negatively correlated to net exports of fossil fuels. Fossil fuel exports (prior to the shock) are set in relation to GDP of the respective region to indicate the importance of the region's economy on fuel exports. This shows a clear pattern: for a shock to the cost in renewable electricity, net exporters of fossil fuels are having much smaller consumption gains than net importers or they even face losses. This pattern is best visible under tax scenario because not only the price but also the quantity of fossil fuel use is affected (see Table 1).

For a shock to CCS, there is a positive trend between the status of being a fossil fuel exporter and consumption change due to a shock (Figure 6). When CCS becomes more affordable, resource owners can benefit from the higher demand of fossil fuels. This holds for all policies with fixed emissions, while there is no clear trend under the tax scenario.

The impact of different shocks for energy exporters and importers can easily be read off from Figures 5 and 6, however, determining the effect of different policies is more complex because it is difficult to attibute the differences to the different channels. Furthermore, the correlation of shocks should be taken into account: all countries are affected by shocks, however, not in the same magnitude. A closer analysis thus needs to take into account how the different regions are affected by the shocks. This analysis is carried out with the help of simple regressions. While not very common

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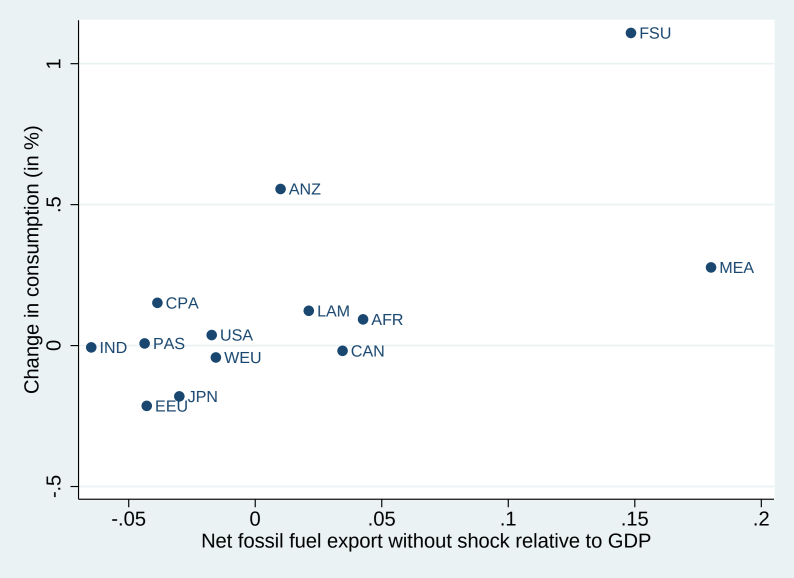
[14] The LES demand system differentiates between basic demand which is not generating utility and other consumption. The consumption level here only refers to the latter.

[15] Changes in consumption are relative to consumption in the same climate policy scenario without the technology shock.

Figure 6: Relation of changes in consumption due to a technology shock in CCS and net energy trade (under no shock situation, relative to GDP) under a quantity based "ntr" policy.



in the CGE literature, this procedure can help to determine factors that drive results a CGE model (see Dixon and Rimmer, 2013, for more information and applications of this method). Identification depends on variation between different regions and years.[16] The method has the advantage of including more dependent variables identified in the theoretical model in Section 2 in the analysis, thus enabling a comparison of how policies affect consumption while controlling for repercussions from the fossil fuel market and the different impact of shocks.

Table 2 shows the regressions for a shock to renewable energy.[17] The direct effects of the shock are captured in two variables. Lower technology costs lead to a higher share in renewable energy in the electricity mix ("change in renewables") and lower cost for existing renewable energy (captured in "pre-shock level of renewables"). The latter is a benefit especially to those countries which have a large share of renewables already in place without a shock. It captures the first term in equations (8), (9) and (12). The former variable should reflect the cost from a additional abatement as captured in the second term of equations (8), (9) and (12) and would be expected to be negative. For all climate policies, there a is significant positive coefficient for both variables. The positive effect also from deployment of additional renewable energy is likely due to a positive learning externality. The shock for renewables is related to the learning rate and as all countries increase their renewable deployment, the global learning progress is increased. This overcompensates countries for the cost of renewable energy deployment. Under all quantity based regimes, the size of the coefficients related to the direct shock impact is very similar. In the tax case it is still positive, yet much smaller than under a quantity based regime.

Energy exporters are only little affected adversely from the shock under all quantity based policies. Under these policies the quantity is not affected and price and thus unit rents decline only slightly.[18] This is however very different in the tax scenario, because of increased abatement supply of fossil fuel is reduced, harming energy exporters. Table 2 also contains regressions on how a shock

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[16] We here use observations for the years 2030 to 2039 as in these years the technology shock is most important, see Figure 4.

[17] All variables referring to levels are in per cent and variables referring to changes are expressed in percentage points, see also the appendix for more details on the variables.

[18] The coefficients are small and significant at the 10% level only in the case of the "ntr" scenario.

Table 2: Different channels influencing consumption change due to a shock in renewable energy.

	no policy	Auction	ntr	CDC	Tax
Change in renewables	0.056***	0.032***	0.035***	0.034***	0.022***
Pre-shock level of renewables	0.000	0.004***	0.004***	0.005***	0.003***
Pre-shock net fossil fuel exports	−0.010***	−0.001	−0.002*	−0.001	−0.012***
Change in emissions	0.051***	0.035***	0.023***	0.026***	0.014***
Pre-shock surplus				−0.003***	
Constant	0.000	0.000	0.000	0.000	0.000
Adjusted R^2	0.765	0.521	0.641	0.709	0.708

Notes: ***/**/* significant at 1%/5%/10%. Each regression has 130 observations (10 years × 13 regions). Variables are described in the appendix.

affects consumption in the absence of climate policy (column "no policy"). In this case the effect on fossil fuels has a similar magnitude as under a tax policy because there is no binding cap and fossil fuel rents and quantity demanded decline as response to a shock.

The change of emissions can be seen as an indicator for the gains of countries less affected by the shock. As demonstrated in Section 2.1, countries not directly affected by the shock can benefit from lower abatement levels (and thus higher emissions). In line with the theoretical model, the coefficient is highest under the auction scenario because a country not (or less) affected by the shock can reduce its abatement efforts without having to compensate other countries. Under quantity based instruments with fixed allocation, the gain for countries not subject to a shock is smaller (as expected) and is even smaller for the price based instrument (theory suggests no effects).

For the CDC regime which is designed such that it includes transfers to poorer countries, there is a negative effect of pre-shock permit surpluses. As expected, the value of the surpluses declines with a lower carbon price and hence the value of emission permits that these countries can sell on the international market.

Figure 7 shows the impact evaluated at variables for the observation of year 2035 for the different regions under the CDC and the tax scenarios (figures for the other policies can be found in the appendix). This indicates the relative importance of the transmission channels. It can be seen that the direct effects of the shock are largest and other factors play a less important role. For India, which has a significant surplus of emission allowances that it can sell, the effect of value decline of surplus emissions is as important as other channels. For industrialized countries who gain via this channel, the effect is of minor importance.

When comparing the CDC scenario with the tax scenario, it is obvious that the energy trade channel is more important in the tax scenario. As emissions are no longer fixed and the tax scheme induces additional abatement, net exporters loose and net importers gain. This leads to a net loss for Russia (FSU) which benefits little from the shock but at the same time loses through reduced fossil fuel rents. When the direct effects are compared, they are smaller in the tax scenario than in the CDC scenario. This is due to the additional cost of additional abatement measures that the technology shock brings along.

Table 3 presents the results of the simple regressions for a shock to CCS. Different from the shock in renewables and more in line with the theoretical model, the direct shock always contains a positive and a negative part. The negative part is associated with the deployment of additional CCS which per se is a cost at first. The positive part refers to lower cost for CCS that would have also be deployed without the shock. Again, the shock coefficients are similar for all quantity based scenarios while they are lower for the price based tax scenario.

The energy channel is more complex in the case of CCS as there is a higher demand for coal and gas (because they can be used in combination with CCS), but a lower demand for oil. This is

Figure 7: Decomposition of consumption changes due to shock in renewable energy in different regions in 2035 under a CDC (top) and a tax (bottom) policy. Calculations based on regressions from Table 2 (for the figure, regressions without a constant were used), “other” refers to residual effects.

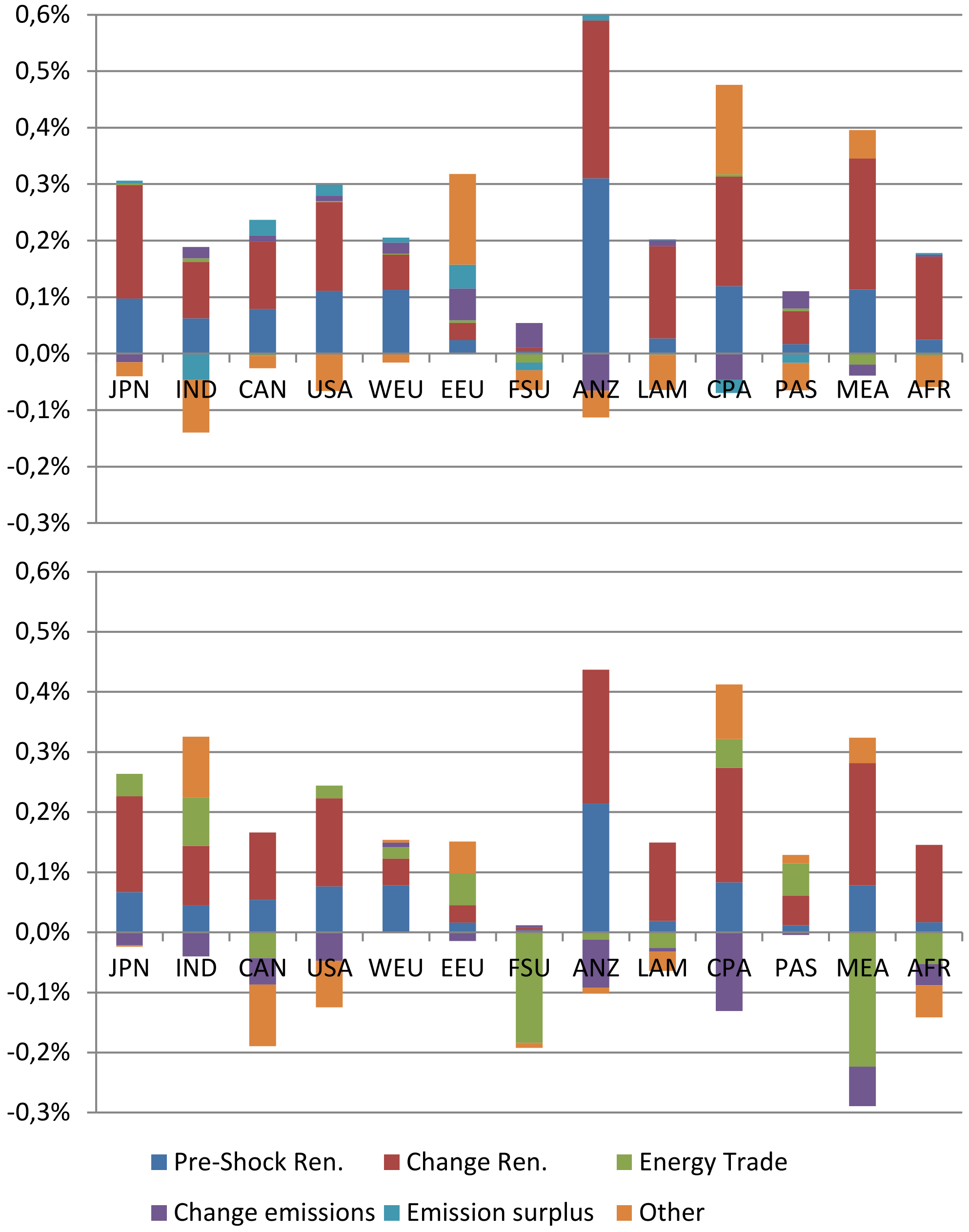

Table 3: Different channels influencing consumption change due to a shock in CCS.

	Auction	ntr	CDC	Tax
Change in CCS	−0.060***	−0.062***	−0.059***	−0.044***
Pre-shock level of CCS	0.008***	0.008***	0.008***	0.006***
Pre-shock net coal exports	0.389***	0.418***	0.467***	0.311***
Pre-shock net gas exports	0.125***	0.125***	0.127***	0.098***
Pre-shock net oil exports	−0.002	0.000	0.002	−0.018***
Change in emissions	−0.023***	−0.045***	−0.059***	−0.016***
Pre-shock surplus			−0.005***	
Constant	0.002***	0.002***	0.002***	0.001***
Adjusted R^2	0.763	0.785	0.862	0.631

Notes: ***/**/* significant at 1%/5%/10%. Each regression has 130 observations (10 years × 13 regions). Variables are described in the appendix.

reflected in the analysis by splitting fossil fuel trade into its components. This confirms that different energy carriers have different effects for net exporters: only coal and gas exporters can benefit, while there is a small loss for oil exporters. Similar as in the case for fossil fuel trade under a shock for renewables, the adverse effect of oil trade is most visible in the tax scenario.

The change in emissions due to the shock is more difficult to interpret than in the case for renewables. This is because lower cost for CCS changes the stable relation between emissions and abatement. In fact, under a tax policy emission even increase slightly despite additional CCS deployment. Under the emission trading with fixed alloaction, additional emissions require to buy additional permits and are hence more costly than in the case of auction or tax.[19] The coefficient for the surplus of emission rights prior to the shock is negative as in the case of a shock to renewable energy cost; again, it is only a minor factor.

Figure 8 shows the impacts of a shock to CCS for different regions in 2035. For different countries, different effects dominate. Australia (ANZ) gains from its coal trade, while other countries gain from reduced cost of CCS which they would have built also in the absence of a shock. There is also a larger difference between benefits from existing CCS and cost from additional CCS deployment. Russia (FSU), for example, is having a relatively high share of CCS already in the baseline leaving less room to increase the share of electricity with CCS.

Compared to a shock to renewables which has a larger positive direct impact, the shock to CCS leaves several countries worse off – even though they all also are facing lower CCS costs.[20] The losses are usually caused by a combination of additional cost from additional abatement and increased cost from energy imports. Note that total direct effects of the shock can be negative. This holds from some regions under the quantity based policies and for almost all regions under the tax policy.

The decomposition based on regression analysis confirms the transmission channels identified in the theoretical model. All coefficients have the anticipated sign, with one exception being the positive effect of additional renewable deployment after a shock. This confirms that a shock reducing abatement cost not only brings along benefits but can also lead to additional costs from additional abatement effort. Different policies and different shock types influence the importance of different transmission channels. In general, the tax regime is most adverse because additional abatement in response to a shock is not compensated for. At the same time, a tax regime does not fix global

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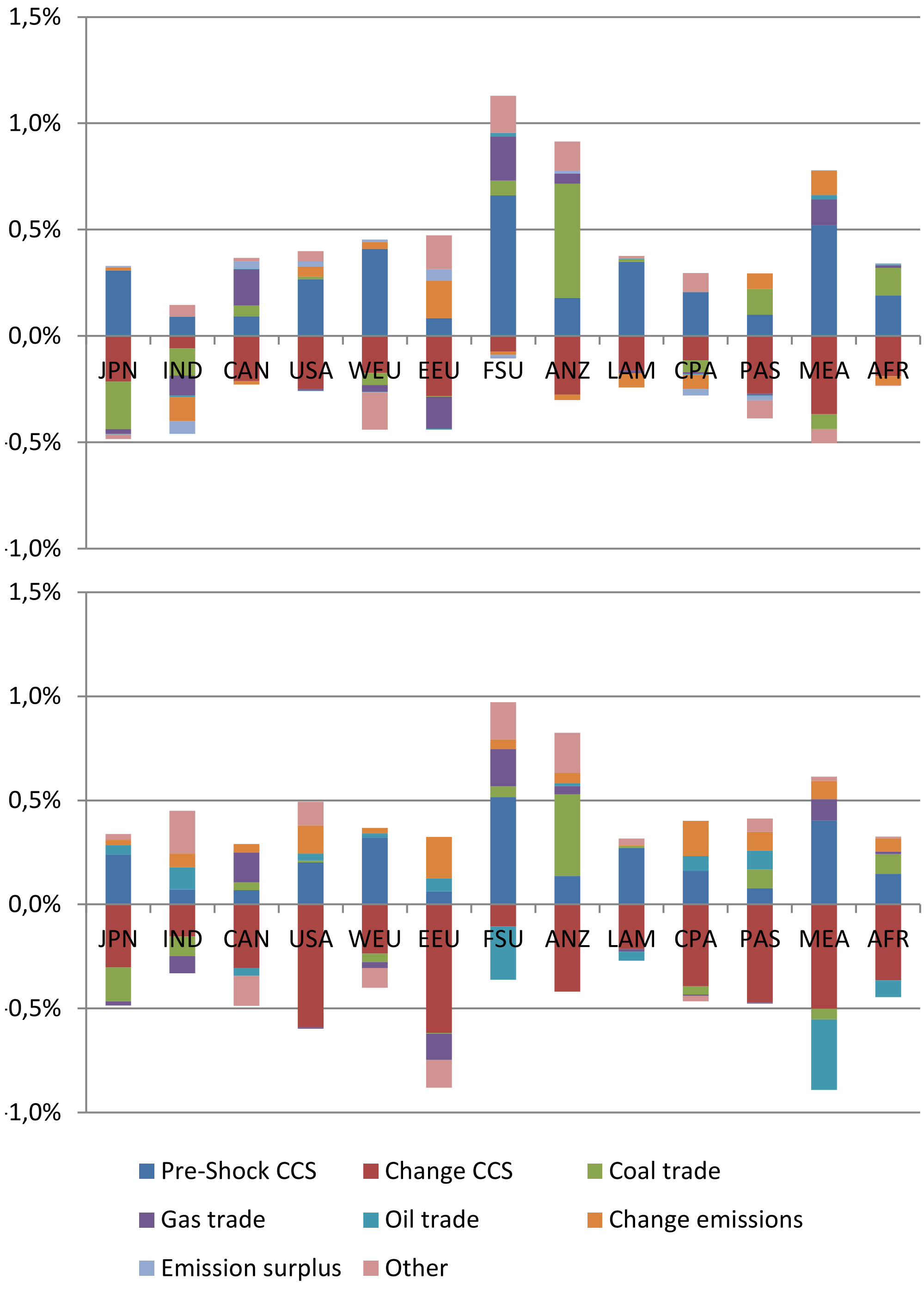
[19] Both in the case of auction and tax, revenues are returned lump sum, while in the case of a fixed allocation there is a transfer to other countries.

[20] Under the auction and ntr schemes, Japan, Canada, Europe (WEU and EEU), and Pacific Asia are worse off. Under CDC, only India and Japan are worse off while in the tax scenario all countries but India, Russia (FSU), Australia (ANZ) and Latin America are worse off.

Figure 8: Decomposition of consumption changes due to shock in CCS in different regions in 2035 under a CDC (top) and a tax (bottom) policy. Calculations based on regressions from Table 3 (for the figure, regressions without a constant were used), "other" refers to residual effects.



emissions and thus fossil fuel exporters are more affected than in quantity based regimes. Under a shock to CCS, energy exporters can gain while the opposite holds for a shock to renewable energy. Under a shock to CCS, for some regions the direct effect from a shock can be negative. This can be reinforced if negative effects from a shock coincide with additional cost from international energy trade. The more complex CGE model thus confirms the theoretic model also in this respect.

4 Conclusions

The model simulations have confirmed the channels identified in the theoretical model. This indicates that it is not necessarily the case that a country or a region gains when its marginal abatement costs are reduced. The main channels for this are repercussions on fossil fuel markets and policies that do not fully compensate for the utilization of reduced cost abatement potential. The latter channel is more pronounced in more flexible policies (tax or auction), i.e. under policies that do not fix emissions allocation but instead a carbon price or a global cap.

Could policies which limit reapping the benefits from lower abatement costs pose a problem? If the country were to be seen as a single actor this might in fact reduce the incentive to innovate. This result is contrary to the seminal paper of Milliman and Prince (1989). The reason for this is the different level of analysis. For an individual firm the incentives might be different compared to a (large) country. One important difference in our setting is that payments for taxes or carbon permit revenues are returned lump-sum to a country, such that paying a tax might be better than engaging in real effort to abate emissions.

While it could be seen that in more flexible systems without fixed allowances a country might not benefit from the reduced cost of its abatement potential, this could also be interpreted as an insurance against higher abatement costs. This paper has looked at a shock towards lower abatement costs, yet the opposite results would hold for a shock towards more costly abatement. In this case, a system without fixed allowances would spread the additional cost of an shock and reduce the direct impact of countries experiencing the shock. There could thus be a tradeoff in policy design between incentivizing innovations and insuring against higher abatement costs.

The results are based on analysis of large countries which can influence global fuel or emission trading markets. In this model, countries do not act strategically. If they were using several instruments in their favor, it can be shown that for large countries a subsidy for renewable energy benefits countries that are importers of emission permits (Eichner and Pethig, 2014). The channel is the price drop in emission permits and the reduced import demand. These channels can also be identified in the model applied here.

The scenario design in this study might be unrealistic in the sence that it fixes policy for several decades. Yet, this is not completely unrealistic, as for example the EU is currently discussing their emissions path until 2030. Along this way however, there might not only be technology shocks but also unexpected macroeconomic shocks. The effect from the stylized technology shocks presented here were relatively small compared overall changes in consumption between now and the year under consideration (2035) and also compared to the primary impacts of climate policy at least in some countries. The overall abatement costs are more sensitive in changes to the overall regime type and a country's status on the fossil fuel markets (exporters vs. importers). Yet, the analysis might also shed some light on the consequences of macroeconomic shocks when these shocks lead to changes in abatement costs. It might therefore be worthwile to explicitly model such shocks to see whether emission policies can act as economic stabilizers.

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A Appendix

A.1 Regions and sectors in the DART model

Table A.1: Regions and sectors of DART

Countries and regions			
WEU	Western Europe	CPA	China, Hong-Kong
EEU	Eastern Europe	IND	India
USA	United States of America	LAM	Latin America
JPN	Japan	PAS	Pacific Asia
CAN	Canada	MEA	Middle East and Norther Africa
ANZ	Australia, New Zealand	AFR	Sub-Saharan Africa
FSU	Former Soviet Union		
Production Sectors/Commodities			
Energy Sectors		**Non-Energy Sectors**	
COL	Coal	AGR	Agricultural Prod.
CRU	Crude Oil	ETS	Energy Intensive Production
GAS	Natural Gas	OTH	Other Manufactures & Services
OIL	Refined Oil Products	CRP	Chemical Products
ELY	Electricity	MOB	Mobility
		OLI	Other light industries
		OHI	Other heavy industries
		SVCS	Services
Renewable and advanced electricity technologies			
WIN	Wind	SOL	Solar
HYD	Hydro	SBIO	Solid Biomass
GASCCS	Advanced Gas with CCS	COLCCS	Advanced Coal with CCS

Note: See also Weitzel (2010) for more information on the modelling approach to include different electricity generation technologies in DART.

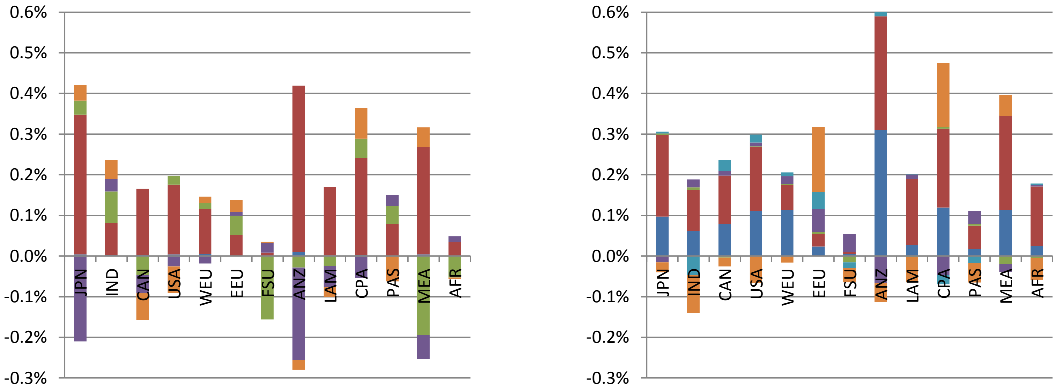
A.2 Variables used in regression analysis

Table A.1: Variables used in regression analysis

Variable name	Description
Change in renewables	Change in the share of solar and wind in the electricity mix in percentage points (relative to the scenario without a shock)
Change in CCS	Change in the share of CCS in the electricity mix in percentage points (relative to the scenario without a shock)
Pre-shock level of renewables	Share of solar and wind in the electricity mix in percent in the scenario without a shock
Pre-shock level of CCS	Share of CCS in the electricity mix in percent in the scenario without a shock
Pre-shock net fossil fuel exports	Value of net fossil fuel export without shock relative to GDP
Pre-shock net coal exports	Value of net coal export without shock relative to GDP
Pre-shock net gas exports	Value of net natural gas export without shock relative to GDP
Pre-shock net oil exports	Value of net export of crude oil and oil products without shock relative to GDP
Change in emissions	Change in emissions in percent (relative to the scenario without a shock)
Pre-shock surplus	Value of emission allowances sold on the international carbon market relative to GDP in the scenario without a shock

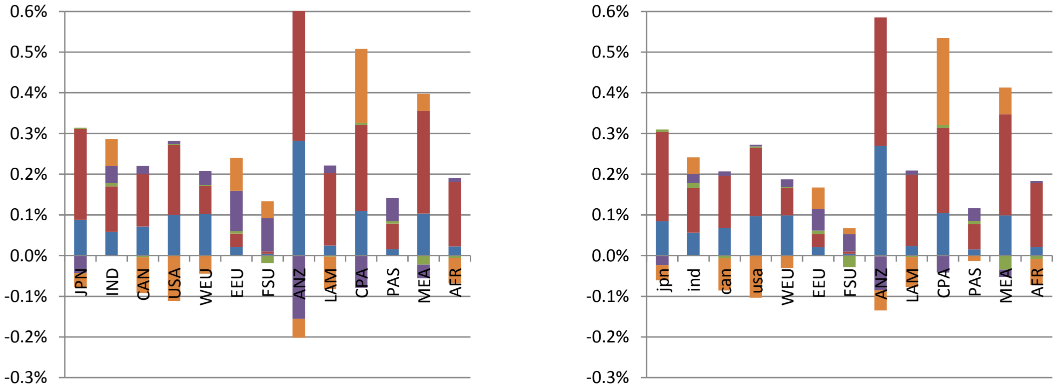
A.3 Decomposition of consumption changes

Figure A.1: Decomposition of consumption changes due to shock in renewable energy technologies in different regions in 2035 for different policies. Calculations for the year 2035 based on regressions from Table 2, “other” refers to residual effects.



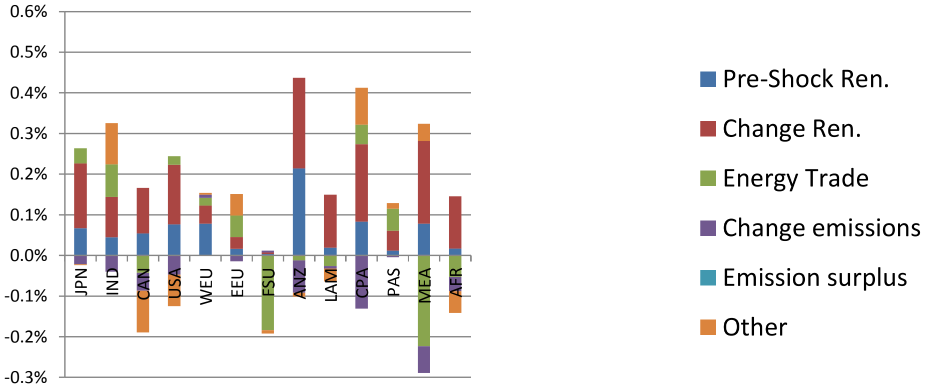
(a) no policy

(b) CDC



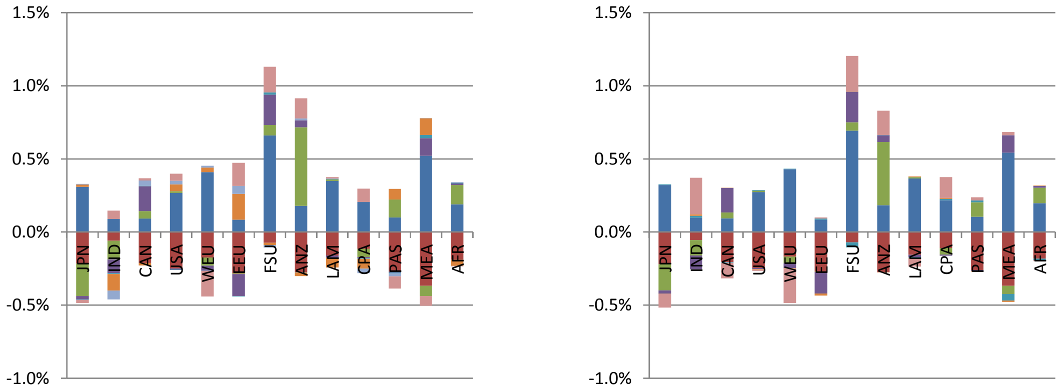
(c) auction

(d) ntr

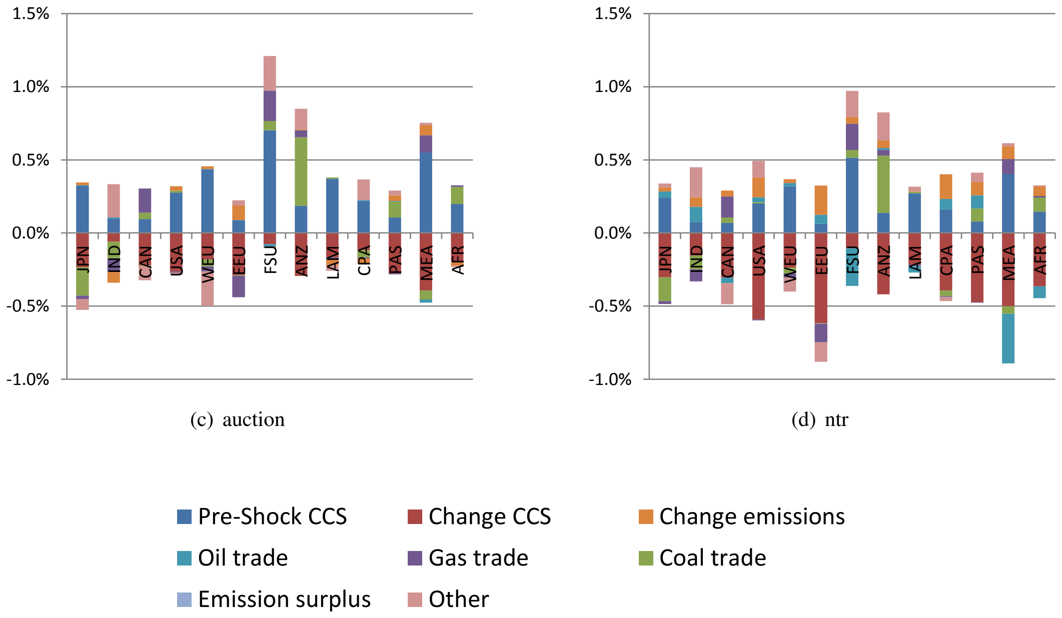


(e) tax

Figure A.2: Decomposition of consumption changes due to shock in CCS in different regions in 2035 for different policies. Calculations for the year 2035 based on regressions from Table 3, "other" refers to residual effects.



(a) no policy (b) CDC



(c) auction (d) ntr