

Boeters, Stefan

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# Optimally Differentiated Carbon Prices for Unilateral Climate Policy

Stefan Boeters\*

CPB, Netherlands Bureau for Economic Policy Analysis, Den Haag

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## Abstract

Economic thought on climate policy as an instance of environmental regulation is strongly influenced by the principle of a uniform carbon price. Economists acknowledge that this principle breaks down in a “second-best” world with other distortions, such as taxes and market power in domestic and international markets. However, systematic analysis of this point in the economic climate policy literature is scarce. In the present paper, a computable general equilibrium (CGE) set-up is chosen in order to examine what pattern of differentiated carbon prices emerges as optimal in a second-best world.

The CGE model WorldScan, which is considered to be representative of the class of models routinely used for numerical climate policy analysis, produces three main results: First, the optimal pattern of carbon prices is highly differentiated, ranging from almost prohibitive taxes to high subsidies (with a range of more than 1700 euros per ton of CO<sub>2</sub>). Second, the welfare gain from switching from a uniform price to optimally differentiated prices is enormous, equivalent to a 27% emission reduction for free. Third, the most important drivers of carbon price differentiation are market power in export markets as well as taxes on consumption, intermediate inputs and domestic output. This shows that carbon price differentiation cannot be dismissed as a policy option lightly. However, before translating these findings into concrete policy advice, the relevant features of modelling pre-existing distortions in CGE models need close revision.

**Keywords:** climate policy, uniform carbon price, carbon price differentiation, optimal taxation, computable general equilibrium model

**JEL codes:** Q42, Q54, H21, H23, D58

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\*Stefan Boeters, CPB, P.O. Box 80510, NL-2508 GM Den Haag, e-mail: s.boeters@cpb.nl. I thank Johannes Bollen, Corjan Brink, Paul Veenendaal and Herman Vollebergh for helpful discussions and suggestions during the course of the project.

# 1 Introduction

If one tenet in environmental economics has over gained a mantra-like status over the years, it is that of “uniform emission pricing”. Theorists have shown that the differentiation of emission prices across time, space or type of emission source makes abatement unnecessarily expensive. Policy advisers – most prominently in climate policy – echo this insight by advocating emission trade schemes that are as encompassing as possible, with a maximum of “where”, “when” and “what” flexibility.

Of course, no environmental economist is as naive as to claim that the “Law of Uniform Emission Pricing” holds in a strict sense. After all, the general optimism in formulating law-like tenets for public policy has been decisively tempered ever since the “General Theory of Second Best”, which essentially claims the *absence* of a general theory for second-best situations (Lipsey and Lancaster, 1956). This is because other distortions in the economy, such as externalities that have been incompletely internalised, a multitude of partial and indirect internalisation options emerge. Indeed, once emission prices are seen as instruments not only for reducing emissions in general, but also for correcting all kinds of pre-existing distortions in the economy, it would be careless to presuppose that a uniform emission price should be the norm.

Even though most environmental economists would readily subscribe to the long list of caveats that accompany the Law of Uniform Emission Pricing, these caveats rarely play a noticeable role in concrete policy advice. Explicitly or – most of the time – implicitly, environmental economists as policy advisers assume that even if the Law of Uniform Emission Pricing is only an *approximation* of optimal climate policy, it remains a *good* approximation. The implicit assumption is that if we were able to calculate optimally differentiated carbon prices, these would deviate little from a uniform price, and the welfare loss from applying such a uniform price instead of optimally differentiated pricing would be small.

Only a small number of theoretical studies explore the case for carbon price differentiation in analytical models (Markusen, 1975; Hoel, 1996). These studies confirm the general second-best result of Lipsey and Lancaster (1956) in the specific setting of emission reduction: once other distortions are present, the simple rules

for optimal policy do not apply any more. However, the analytical expressions that characterise the optimum in a second-best model quickly become so complicated that it is difficult to tell even the direction of the deviation. Formulas that would be informative about the costs of deviating from the optimum are even more complex and thus scarcely derived in previous analytical papers.

The appropriate follow-up in situations where analytical expressions no longer lend themselves to interpretation is numerical modelling. Surprisingly, to my knowledge only a single paper addresses carbon price differentiation numerically, namely the paper by Böhringer, Lange and Rutherford (2010).<sup>1</sup> For two regions, the EU and the US, these authors explore whether carbon price differentiation raises welfare. However, they account for a single degree of freedom only. The unilaterally abating region may use two carbon prices for energy-intensive industries and the rest of the economy. In this restricted setting, two incentives for carbon price differentiation are distinguished and explored, namely the strategic use of market power in international trade (terms-of-trade effects) and compensation for leakage. The overall conclusion drawn by Böhringer et al. (2010, p. 2) is that the differentiation in carbon prices that can be motivated by such market imperfections is moderate and that the welfare gain attainable by exploiting carbon price differentiation is negligible.

The conclusions drawn from the simulations with the computable general equilibrium (CGE) model WorldScan in this paper are strikingly different from those in Böhringer et al. (2010). By solving for welfare-maximising differentiated carbon prices, I obtain widely diverging prices that range from high subsidies to virtually prohibitive taxes. I also show that huge welfare gains are possible by exploiting the implied inefficiencies of a uniform carbon price. These gains are equivalent to a 27% reduction in carbon emissions for free. However, these results should not be misunderstood as direct policy advice. In the body of this paper, I decompose the effects at work and explain their components as far as possible, but many questions remain unanswered. The presented findings are best understood as a counterpoint to Böhringer et al.'s (2010) message that carbon price differentiation is almost irrel-

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<sup>1</sup>Actually, Markusen (1975) backs up his argument with numerical simulations as well. However, in these simulations he simply compares different policy mixes, without determining an optimum. Recently, Böhringer and Alexeeva-Talebi (2012) used a similar set-up to that presented in Böhringer et al. (2010) to study competitiveness issues.

evant. They mark the range of possible model results and call for more contributions by applied modellers.

From the set-ups of these two studies (Böhringer et al., 2010, and the present paper), two clear candidates for explaining the differences in the model results emerge. First, in the simulations of the present paper, carbon prices are allowed to vary in two dimensions, by sector and by fuel, in considerable sectoral detail. It turns out that “energy-intensive” versus “non-energy-intensive” is not a good discrimination criterion for high versus low carbon prices. Second, WorldScan, the model used in the present study, contains the full range of tax distortions captured by the GTAP data set (input taxes, output taxes, consumption taxes and tariffs in international trade). These were neglected in Böhringer et al.’s (2010) study.<sup>2</sup> I show that pre-existing intermediate input taxes, consumption taxes and output taxes are particularly important drivers of differentiation in the pattern of optimal carbon prices.

The remainder of this paper is organised as follows. In Section 2, the model and scenario settings are introduced. Section 3 presents the simulations with the derivation of optimally differentiated carbon prices and the decomposition into driving forces (pre-existing distortions). Section 4 shows in an explorative and exemplary fashion how the model results change once we deviate from the conventional modelling practice of conceptualising pre-existing taxes as pure distortions. Section 5 contains a summary and concludes.

## 2 Model and scenarios

WorldScan, the model used for the quantitative simulations, is similar to a number of other CGE models used on a regular basis to assess world-wide climate policy (e.g. MIT-EPPA; Paltsev et al., 2005). It is a multi-region, multi-sector, recursively dynamic CGE model based on the GTAP7 data set (Badri and Walmsley, 2008) with the base year 2004.<sup>3</sup> The details of the model are described in Lejour et al.

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<sup>2</sup>Böhringer et al. (2010) are not explicit about this. However, it is implied by the fact that uniform carbon prices are actually optimal in their model when carbon leakage and terms-of-trade effects are switched off (Scenario “None”, p. 15).

<sup>3</sup>During the course of the project, the GTAP8 data set (base year 2007) became available. However, as the point of the present paper is a rather general one and not dependent on the details

(2006). Here we use an extension with a bottom-up representation of the electricity sector, as documented in Boeters and Koornneef (2011).

The aggregation of regions and sectors can be flexibly adjusted in WorldScan. I use a version with nine regions and sixteen sectors, as listed in Tables 1 and 2. Regional disaggregation is relatively coarse, the EU – as the proponent of unilateral climate policy in the presented simulations – is treated as one homogeneous region.<sup>4</sup> Sectoral disaggregation has a focus on the energy-related sectors, whereas other sectors are captured in a more aggregated manner. The electricity sector has a bottom-up structure, namely five separate technologies with increasing marginal costs, whose output is perfectly substitutable (see Table 3 and Boeters and Koornneef, 2011).

Table 1: Regions in WorldScan

European Union	USA
Other OECD	Brazil
China	India
Other SE Asia	Former Soviet Union
Rest of the World	

Table 2: Sectors in WorldScan

AFF	Agriculture, forestry, fishing	COA	Coal
OIL	Oil	GGD	Gas and gas distribution
CNP	Consumer products	PPP	Paper products and publishing
PCP	Petroleum and coal products	CRP	Chemical, rubber, plastic products
MMP	Minerals and mineral products	MET	Metals
CGD	Capital goods and durables	ELY	Electricity
RRT	Road and rail transport	WTP	Water transport
ATP	Air transport	NTS	Non-transport services

The discussion of carbon price differentiation below is in terms of “carbon sources”. Sixteen sectors plus final consumption (FCN) times three fuels (coal, natural gas of the initial situation, there is no particular value added from updating the data base adopted.

<sup>4</sup>Determining the optimal *regional* differentiation of carbon prices within Europe would add a further dimension to the problem; however, this is outside the scope of the present paper.

Table 3: Baseline: EU electricity production

Generation technology	Share (%) in 2004	Share (%) in 2020
Fossil	62.6	66.5
Nuclear	23.1	20.4
Hydropower	7.6	6.8
Wind & sun	2.1	2.1
Biomass	4.5	4.1

and petroleum products) results in 51 potential sources of CO<sub>2</sub> emissions. All sources that have a share of less than 0.1 % of total emissions are disregarded in the simulation. The remaining 36 sources cover 99.6 % of all baseline emissions in 2020, with the largest shares in the electricity generation, transport and refinery sectors (see Table 4). The fuel split of the 36 sources analysed is nine for coal, thirteen for gas and fourteen for petroleum products. Two sectors (i.e., COA and OIL) completely disappear from the analysis, because none of their sources is above the critical level.

Table 4: Emission sources in the EU (% in total CO<sub>2</sub> emissions)

	Coal	Natural gas	Petroleum prod.
AFF	–	0.2	1.1
COA	–	–	–
OIL	–	–	–
GGD	–	0.2	–
CNP	0.2	1.2	0.6
PPP	0.1	0.6	0.2
PCP	4.8	1.1	7.7
CRP	0.2	2.0	5.0
MMP	0.6	1.3	1.2
MET	0.2	0.8	0.9
CGD	–	0.8	0.4
ELY	21.1	6.7	2.2
RRT	–	0.2	12.6
WTP	–	–	2.0
ATP	–	–	3.7
NTS	0.1	2.8	2.3
FCN	0.5	5.4	8.8

## Baseline

WorldScan is set up to analyse deviations from a baseline (“business as usual”) path. This path is not generated by WorldScan itself, but derived from other models or scenario studies. In the present case, the baseline is taken from the Environmental Outlook 2008 scenario generated with the TIMER model of the Netherlands Environmental Assessment Agency (OECD, 2008), updated for growth changes throughout the global credit crisis of 2009/2010.

The baseline calibration uses time series for population and GDP by region, energy use by region and energy carrier, and world fossil fuel prices by energy carrier. Population is an exogenous input into the model. The other time series are reproduced by adjusting the corresponding model parameters. These are total factor productivity (differentiated by sector) for GDP, autonomous energy efficiency for energy quantities, and the amount of natural resources available as an input into fossil fuel production for energy prices.

Table 5 lists important baseline indicators for the EU in 2020 (relative to 2004). The mix of fossil fuels remains roughly stable, while total CO<sub>2</sub> emissions are decreasing by 0.2 % per year. The latter is a consequence of the falling energy intensity of the economy, driven by a shift away from the most energy-intensive sectors. The bottom rows of Table 5 show the underlying real fuel prices (relative to the EU consumption price index). Relative fuel prices remain stable, whereas the overall increase in the fossil fuel price level contributes to the reduction in energy intensity.<sup>5</sup>

## Scenarios

The common denominator of all the scenarios examined in Section 3 is a 20 % reduction in CO<sub>2</sub> emissions in the EU.<sup>6</sup> I compare the reference case of a uniform emission price with the case of emission prices that are optimally differentiated across fuels and sectors. An important part of the body of the paper consists of decomposition scenarios. In these scenarios, all distortions except one are eliminated from the model. This approach can determine the degree of carbon price differentiation

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<sup>5</sup>Appendix A.1 shows the results for a different set of baseline assumptions, which were used in an earlier version of this paper. It turns out that these assumptions hardly affect the pattern of optimally differentiated carbon prices.

<sup>6</sup>This setting is inspired by the model comparison exercise in Round 22 of the Energy Modeling Forum (Böhringer et al., 2009). Because the “20/20/20” target of the EU is a heavily researched scenario, it seems an appropriate setting to place the simulations in the present paper into perspective.



Table 5: Baseline in 2020: Quantities and prices

Economic indicators	2020 value as a multiple of 2004	Yearly growth 2004-2020 (%)
Population	1.051	0.3
Real GDP	1.281	1.6
Fossil energy use	0.975	-0.2
Oil	0.980	-0.1
Natural gas	0.964	-0.2
Coal	0.979	-0.1
Electricity use	1.123	0.7
CO <sub>2</sub> emissions	0.973	-0.2
Fossil energy intensity	0.761	-1.7
Fossil energy prices		
Oil	2.046	4.6
Natural gas	1.737	3.5
Coal	1.734	3.5

that can be justified by one distortion alone. The decomposition also allows us to ascertain which distortions are driving the results, and which lead to only minor adjustments.

Finally, in Section 4, two additional scenarios follow that can be read as a – albeit partial – sensitivity analysis. In these scenarios, I interpret excise taxes on fossil fuels as a joint input into the consumption of transport services, rather than as a pure distortion. In this way, it is clarified that there is scope for the interpretation of the tax figures in the data, which has consequences for the structure of optimally differentiated carbon prices.

## 3 Results

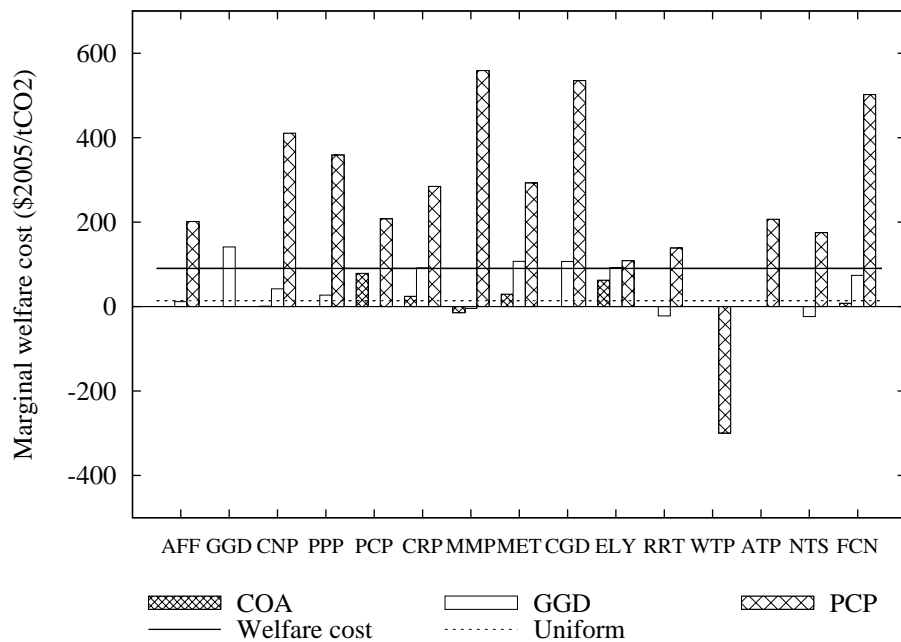
### 3.1 Optimally differentiated CO<sub>2</sub> prices

The point of departure for the simulations is the projected baseline situation in 2020 (see Figure 5). As the reference case, I simulate a 20 % reduction in CO<sub>2</sub> emissions with respect to the baseline in the EU, implemented by a uniform carbon price across all sources (sectors and fuels). This uniform carbon price turns out to be 14

euros per ton of CO<sub>2</sub>.<sup>7</sup> The motivating question of the present paper is whether we can improve upon this situation by differentiating carbon prices by source.

As a first indication of whether the uniform price is close to, or far away from, the optimum under price differentiation, I calculate the marginal welfare cost of the emission price by source. This calculation is carried out by increasing the emission price for one source, and holding the prices of all other sources fixed, and then repeating for each of the analysed sources. The resulting welfare change (Hicksian equivalent variation for the change in the consumption of the representative EU consumer) is divided by the resulting overall change in emissions (from all sources together). The result of this calculation is in euros per ton of CO<sub>2</sub> and can be directly compared with the uniform emission price. Figure 1 shows the marginal welfare costs for the 36 largest sources, which cover more than 99.6 % of all emissions (see Section 2). As also noted earlier, two sectors (i.e., COA and OIL) completely disappear from the graph, because none of their sources is above the critical level.

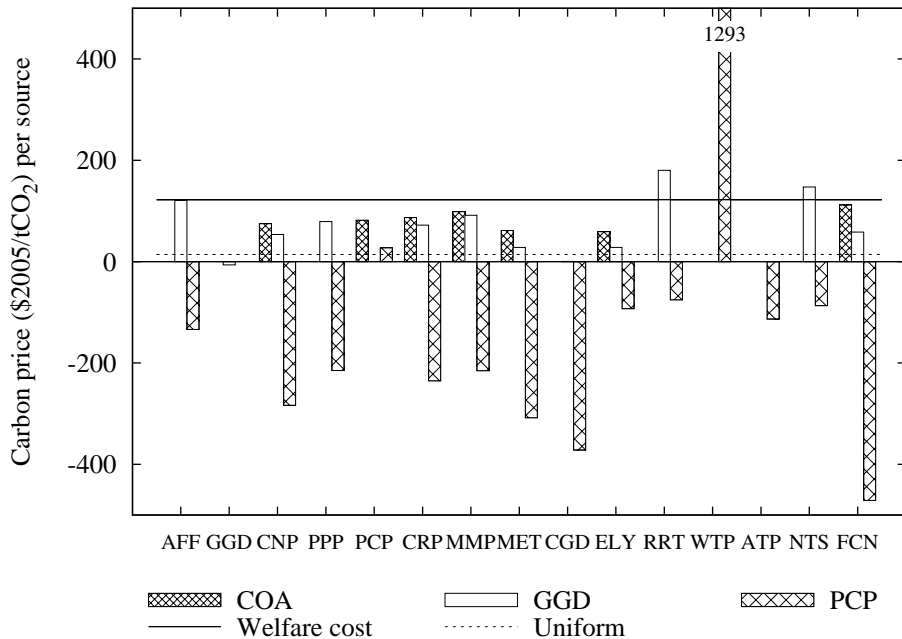
Figure 1: Marginal costs of the uniform emission price



The range of marginal welfare costs is huge. Welfare costs are highest for pet-

<sup>7</sup>This is close to the price of 17 euros calculated in Boeters and Koornneef (2011) under slightly different assumptions. The WorldScan emission prices are often at the lower end of the spectrum of the results from similar models (compare the results in Böhringer et al., 2009).

Figure 2: Optimally differentiated emission prices



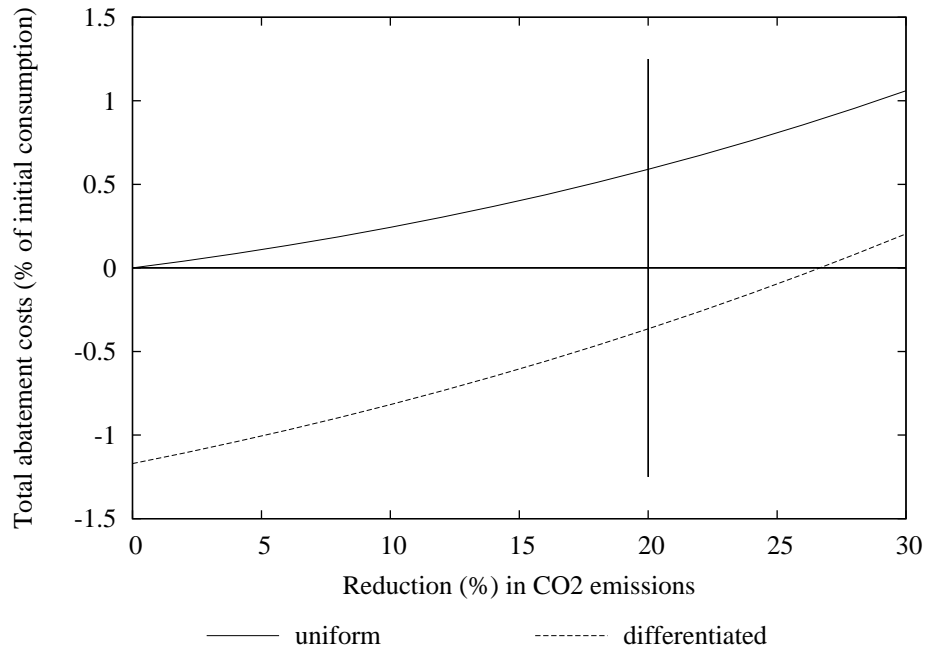
roleum and coal products (PCP) in minerals and mineral products (MMP) with 558 €/tCO<sub>2</sub> and lowest, even negative, for PCP in water transport (WTP) with -300 €/tCO<sub>2</sub>. For several other sources the marginal welfare costs are negative as well, even if only slightly so. Negative welfare costs mean that reducing CO<sub>2</sub> for the respective sources would increase economic welfare. The overall range of marginal welfare costs is more than 850 €/tCO<sub>2</sub>, indicating a huge potential for welfare gains through carbon price differentiation.

Almost all the marginal welfare costs presented in Figure 1 are higher than the uniform price (dashed line at 14 €/tCO<sub>2</sub>), which may seem puzzling at first glance. However, the relevant standard of comparison is not the uniform carbon price itself, but rather its marginal welfare cost.<sup>8</sup> The marginal welfare cost of the uniform carbon price is 90 €/tCO<sub>2</sub>, as indicated by the solid line in Figure 1. We can see that roughly half of the source-specific marginal welfare costs are below or above this reference.

Optimally differentiated emission prices are calculated by equalising marginal

<sup>8</sup>This distinction is sometimes burred in the literature on carbon pricing. The marginal welfare cost of the carbon price is calculated by increasing the uniform price marginally and dividing the resulting change in welfare by the resulting change in emissions.

Figure 3: Abatement costs



welfare costs across all sources.<sup>9</sup> The result (shown in Figure 2) is, as a rough approximation, a mirror image of Figure 1. Where the marginal welfare costs of the uniform price are high (PCP as an input into many sectors), optimal prices are low (a subsidy of up to 500 €/tCO<sub>2</sub>) and vice versa. Overall, it is optimal to subsidise 13 of the 36 sources, almost exclusively PCP. The highest carbon price, however, is for oil as well (1293 €/tCO<sub>2</sub> in WTP). With these optimally differentiated carbon prices, the marginal welfare cost – uniform across sources – turns out to be 122 €/tCO<sub>2</sub> (see the solid horizontal line in Figure 1).

At first glance, it is puzzling that the marginal welfare cost of optimally differentiated carbon prices (122 €/tCO<sub>2</sub>) is higher than that of the uniform price (90 €/tCO<sub>2</sub>). How does this concur with the fact that, by construction, the *absolute* costs of a uniform emission price must be lower?

<sup>9</sup>As the model is set up as a mixed complementarity problem (MCP), welfare cannot explicitly be maximised. In determining the optimally differentiated prices, I employ an iterative procedure. First, all carbon prices are individually adjusted so that their marginal welfare costs equal the marginal cost of a proportional adjustment in all prices one iteration step before. Second, the overall level of carbon prices is (proportionally) adjusted so that the emission reduction target is met. Third, the marginal welfare cost of a proportional adjustment is calculated. These steps are iterated until convergence. Depending on the scenario, convergence can require up to 50 iterations.

Figure 3 shows total abatement costs for varying levels of emission reductions (up to 30%) with either uniform or differentiated emission pricing. Both curves are increasing and convex, as expected. Attaining the target of a 20% reduction (vertical line) through the introduction of a uniform emission price costs 0.6% of initial consumption, whereas using differentiated carbon prices instead results in a welfare gain of 0.4%. Implementing an emission-neutral, optimal carbon tax-and-transfer system in the original situation would generate a welfare gain of even 1.2%. Put differently, by using optimally differentiated carbon prices, a 27% reduction in CO<sub>2</sub> emissions can be achieved without a decrease in welfare. As there is a *discrete* welfare gain by switching from a uniform carbon price to differentiated pricing, it is no contradiction to state that differentiated prices have higher *marginal* welfare costs. This is demonstrated in Figure 3: for any given level of abatement, the curve for differentiated prices is slightly steeper than that for the uniform price. In other words, the higher the abatement level, the lower is the welfare gain of an emission-neutral switch from uniform to differentiated pricing.

### 3.2 Decomposition

In the previous subsection, I presented the pattern of optimally differentiated carbon prices derived from the WorldScan model. In a broad sense, we know that pre-existing tax distortions and market power in international trade are responsible for the deviation from uniform carbon pricing. However, we do not yet know which *particular* distortions are responsible for the pattern that emerges in Figure 2. In this subsection, I elucidate the role of specific distortions by performing a series of decomposition exercises. In each of these exercises, all distortions but one are eliminated from the model, and the optimal pattern of differentiated carbon prices is re-calculated. Possible interaction effects notwithstanding, the pattern in Figure 2 should then be interpretable as the sum of the effects of individual distortions.

The procedure for eliminating distortions from the model differs by distortion. In the case of market power in international trade, I add the assumption that the EU is unable to influence international import and export prices. In the model, this is implemented through import and export taxes on trade partners, which are adjusted in order to keep constant the prices incurred by the EU. The EU then acts

as a small open economy.<sup>10</sup> In the case of taxes, I run model versions that include a preparatory counterfactual where taxes (except for the one focused on) are set to zero. The resulting situation is used as the point of departure for climate policy.<sup>11</sup>

### 3.2.1 Market power in international markets

We start with the cases of market power in the import and export markets. In the first model variation, we focus on import power, i.e. the opportunity to influence import prices through a carbon tax. All taxes are set to zero, and export prices are held constant at their initial levels through an endogenously adjusting import tax/subsidy on trade partners. The resulting pattern of optimal carbon prices is depicted in Figure 4. Overall, the price differentiation induced by import power is moderate. Energy inputs into the gas (GGD) and metals (MET) sectors are taxed significantly below the average level, while there is also a systematic pattern of pricing emissions from COA lower than from GGD and PCP, but the latter differences are rather small.

Two general features in Figure 4 deserve attention. First, the uniform carbon price necessary to achieve the 20 % reduction goal is 191 €/tCO<sub>2</sub>, considerably higher than in the base case presented in Section 3.1. The reason for this finding is that removing all taxes from the model expands the economy in general and emissions in particular. Driving emissions back below the initial level requires additional effort, captured by the carbon price.<sup>12</sup> Second, in contrast to the base case shown in Section 3.1, the marginal welfare cost of the uniform carbon price (142 €/tCO<sub>2</sub>, not shown in the figure) is now *below* the uniform price. This is the direct consequence of the market power in import markets. Market power means that carbon prices not only reduce emissions, but also reduce import prices by reducing import demand.<sup>13</sup> Again,

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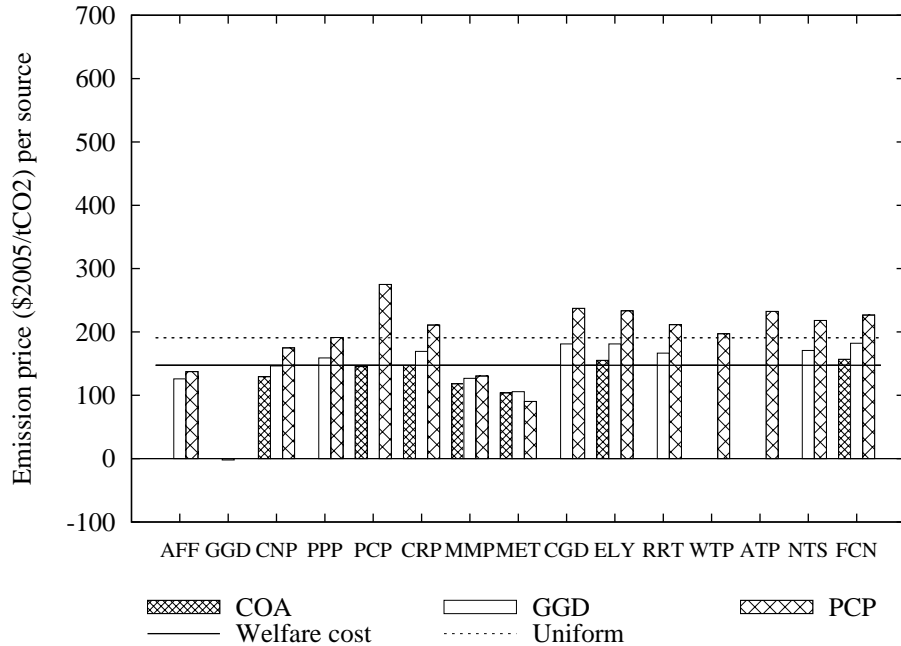
<sup>10</sup>Böhringer et al. (2010) use a different decomposition strategy. For eliminating terms-of-trade effects, they assume that the abating region must compensate their trade partners for welfare changes incurred because of climate policy.

<sup>11</sup>The counterfactual situations in which a subset of taxes is set to zero differ from the original model in total emissions. (Normally, as distortions are removed, economic activity and thus emissions would be higher.) Therefore the overall level of carbon prices is not comparable across models. Still, price differentials between sources can be interpreted in the desired way.

<sup>12</sup>The 20 % reduction goal is still defined with respect to the baseline situation *with* pre-existing taxes.

<sup>13</sup>This effect is also present in the basic model, but it is overridden by the negative effects of tax distortions.

Figure 4: Import market power



the marginal welfare costs of optimally differentiated carbon prices (147 €/tCO<sub>2</sub>) are slightly above those of the uniform price.

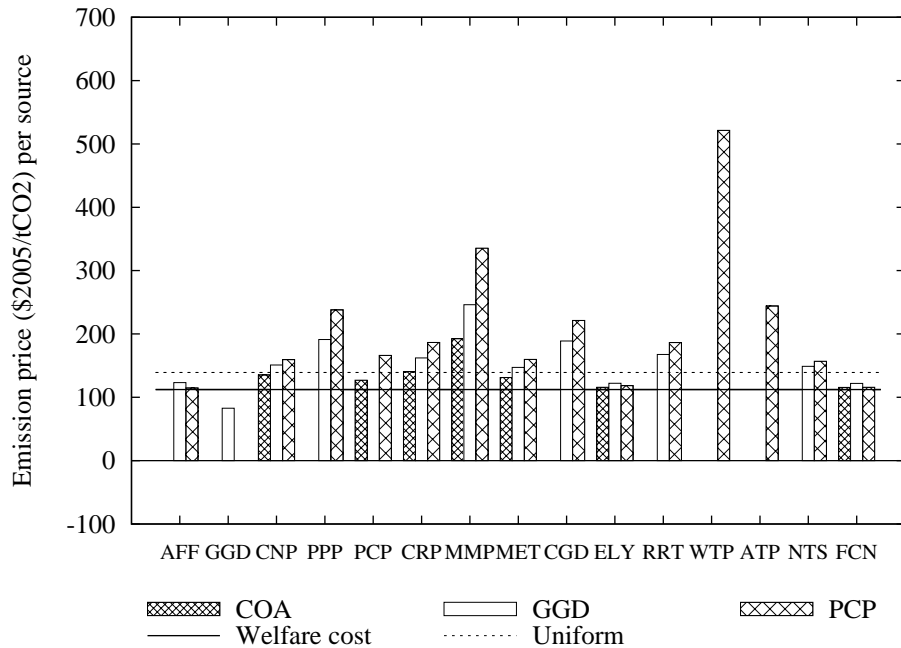
The mirror image of the case presented in Section 4 is market power in export markets. Again, all pre-existing taxes are set to zero. Further, import prices are fixed at their initial levels through an endogenously adjusting export tax in non-European regions, whereas export prices are free. The resulting pattern of optimal carbon prices is shown in Figure 5.

Compared with market power in import markets (Section 3.2.1), the effects on the differentiation of optimal carbon prices is now significant. Particularly striking is the high tax rate on PCP use in WTP. However, taxes on fuel use in the PPP, MMP and ATP sectors are also considerably above the uniform tax rate. Again, the marginal welfare costs of the uniform price (112 €/tCO<sub>2</sub>) is below this price itself.

### 3.2.2 Pre-existing taxes

Besides market power in international trade, pre-existing taxes form a second set of reasons for deviations from the uniform carbon price. In this section, I focus on three

Figure 5: Export market power



types of taxes: intermediate input taxes, consumption taxes and output taxes.<sup>14</sup>

A preliminary model version is run, in which all other taxes are removed, in order to isolate the effects of a particular set of taxes. From this starting point, the usual numerical procedure described in Footnote 9 is carried out. Carbon prices are varied by source, with import and export prices fixed to eliminate trade effects.

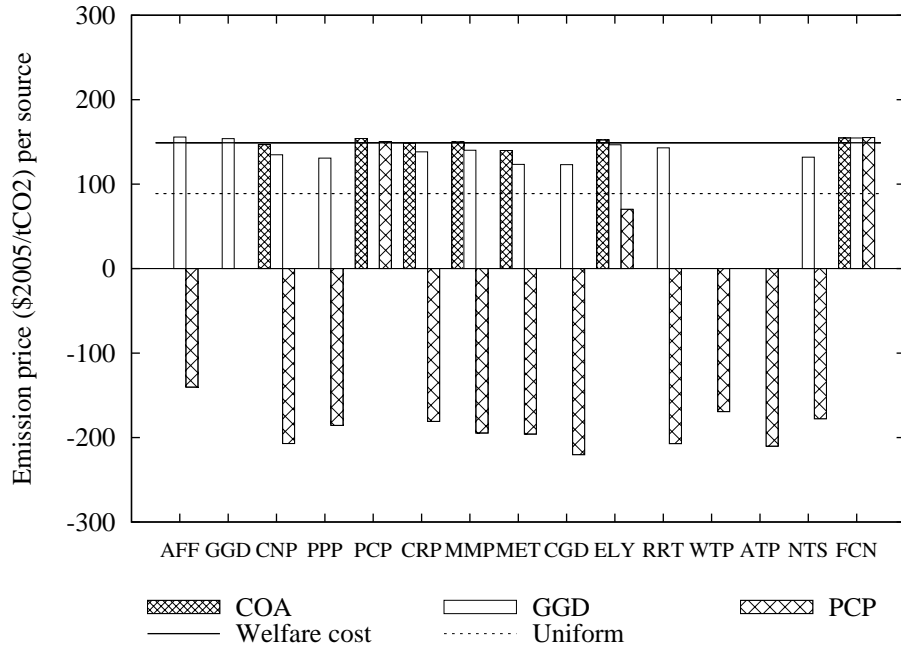
Figure 6 shows the consequences of pre-existing intermediate input taxes for the optimal structure of carbon prices. There is one clearly dominating effect, which stems from the intermediate input taxes on refined fuels (PCP). As intermediate input taxes on carbon sources are economically indistinguishable from carbon prices, any difference in these taxes is compensated by optimal carbon prices.<sup>15</sup> The high subsidies on PCP inputs in Figure 6 can thus be interpreted as a rebate of that part

<sup>14</sup>In addition, WorldScan contains import and export tariffs as well as taxes on the primary factors of production and investment. These are disregarded in the analysis that follows. Import and export tariffs are small for the EU and affect the pattern of optimal carbon taxes only marginally. Income taxes amount to lump-sum taxes without any distortionary effect in the model set-up, because the supply of primary production factors is fixed. Moreover, investment taxes can be disregarded because the simulations are based on a static model version for 2020.

<sup>15</sup>This compensation is imprecise, because there are indirect effects of taxes on other intermediate input as well. However, because those effects are small, the overall picture is dominated by the intermediate input taxes on fuels.



Figure 6: Intermediate input taxes



of excise tax payments on transport fuels that exceeds the optimal carbon price level. The only sectors where this does not apply are those where the fuel input is not primarily for transport purposes (i.e. PCP, ELY).

The case of consumption taxes (Figure 7) is straightforward. There are high pre-existing taxes on the private consumption of fuels, in particular on transport fuels as before. In an optimally differentiated system of carbon prices, this would be reflected by a high compensatory subsidy. There is some spillover on carbon prices in production as well, but this is relatively small.

Finally, we turn to pre-existing output taxes. Again, carbon prices must serve the double role of both regulating emissions and – as far as possible – correcting existing tax distortions. With output taxes, a correction can work in two ways. First, carbon prices on a sectoral input are used to counteract output subsidies in the same sector. This can be illustrated with the case of WTP. The EU output subsidy to WTP in the GTAP data base is 21 % (for comparison: rail and road transport (RRT) 5 % subsidy, air transport (ATP) 2 % tax). Second, carbon prices on fossil fuel inputs counteract output taxes on the production of these fuels. This is reflected in the consistent pattern of carbon prices by fuel in each sector, namely highest for coal

Figure 7: Consumption taxes

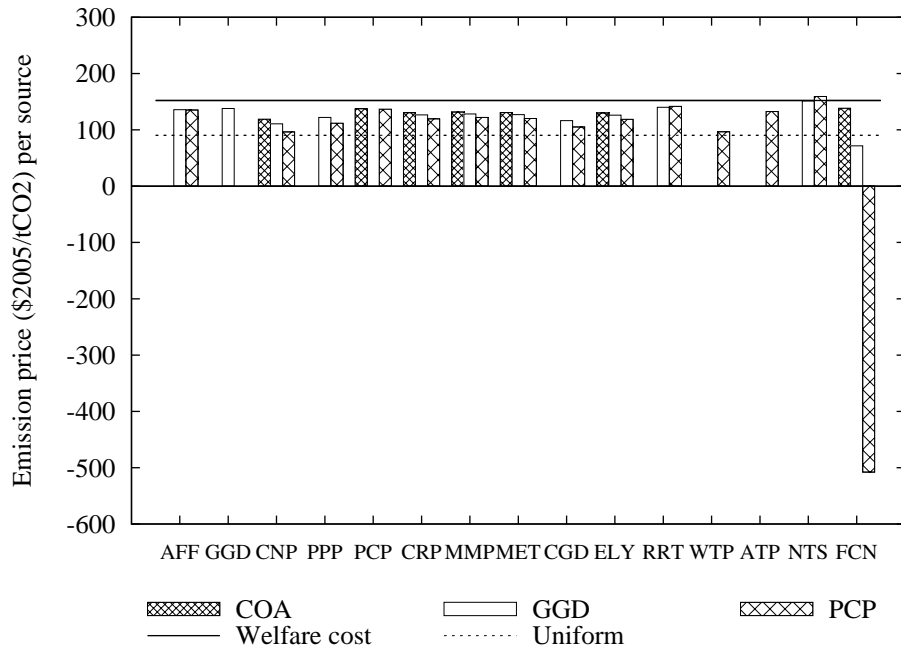
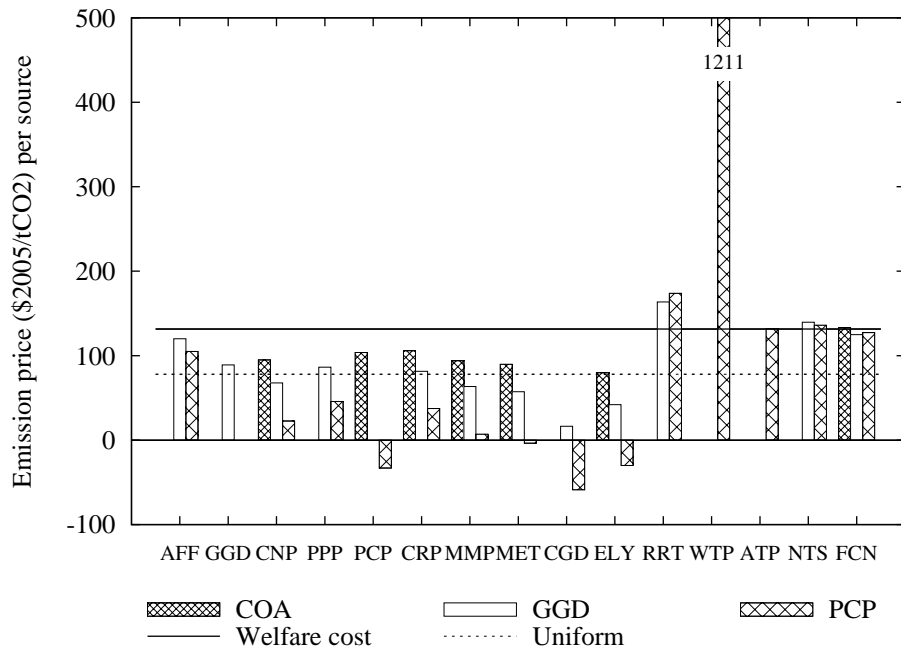


Figure 8: Output taxes



and lowest (or even negative) for PCP. Here the respective tax rates from the GTAP database are a 20% subsidy on COA, 7% tax on GGD and 12% tax on PCP.

### 3.2.3 Summary of the decomposition exercise

Apart from the five distortions analysed in detail in previous subsections, WorldScan contains five smaller distortions, which must be removed in order to arrive at a clear-cut first-best world. This set of smaller distortions consists of imperfect capital mobility, endogenous international transfers and three types of taxes: on imports, exports and investment. Their effect on the pattern of optimal carbon prices is negligible, however, and thus focus on the five main distortions in Sections 3.2.1 and 3.2.2 is justified.

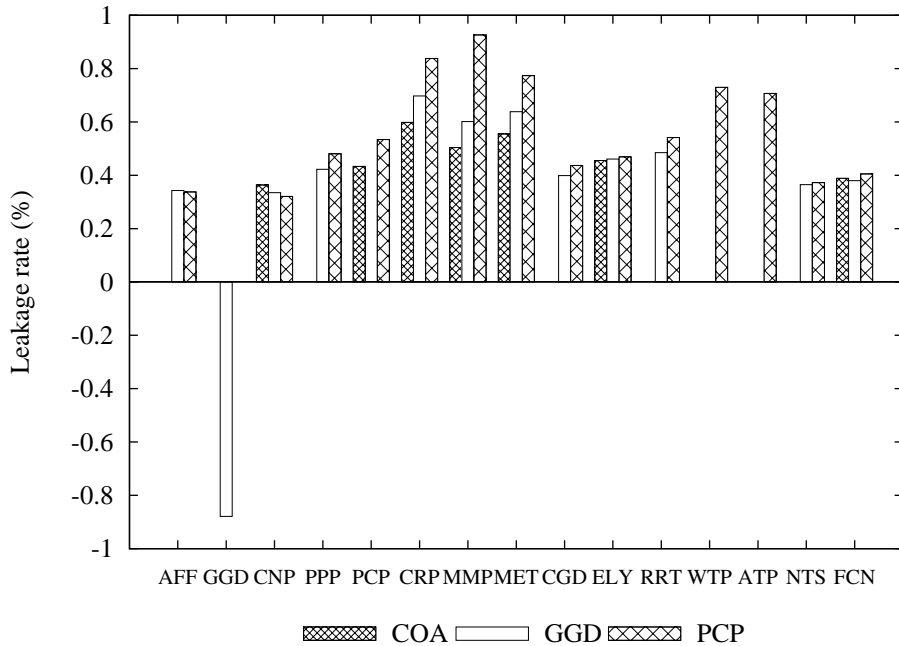
Reassuringly, removing all ten distortions (five major and five minor) from the model produces a first-best world, in which a uniform carbon price is optimal. Performing the marginal evaluation that underlies Figure 1 in this first-best model produces marginal welfare costs that are uniform across sources to a high degree of numerical accuracy. Even though marginal welfare costs are calculated by dividing tiny changes in welfare by similarly tiny changes in emissions, the variation in marginal costs across sources remains below one euro per ton of CO<sub>2</sub>.

The decomposition exercises discussed in Sections 3.2.1 and 3.2.2 aimed to explain the pattern of optimal carbon prices presented in Figure 2. They showed that although a large number of effects are interacting, a small subset of them is dominating quantitatively. The results stand out. First, the extremely high carbon price for WTP is a combination of the attempt to benefit from export market power (Figure 5) and to counteract the distortions caused by output subsidies (Figure 8). Second, low and in most cases negative carbon prices for refined fuels (PCP) reflect pre-existing intermediate input and consumption taxes on these fuels. Third, the high carbon prices for gas inputs into RRT and NTS are again driven by the pattern of output taxes (Figure 8).

## 3.3 Leakage

The EU climate policy discussed in Sections 3.1 and 3.2 was “domestic” in a narrowly defined sense, namely that the reduction target was expressed in terms of EU emissions only, while the emissions in other regions were ignored. However, car-

Figure 9: Leakage rates



bon leakage is one of the most discussed issues in international climate policy<sup>16</sup>. A natural follow-up step consists therefore in the coverage of emissions from all regions. How do the results change if the reduction target is rather expressed in global emissions?<sup>17</sup>

As a preliminary step, Figure 9 shows marginal leakage rates by source, which have been computed in the following way. We start from the optimally differentiated carbon prices in Figure 2.<sup>18</sup> Then carbon prices are marginally increased, source by source, and the leakage rate is calculated as

$$\text{leakage rate} = 1 - \frac{\text{change in world emissions}}{\text{change in domestic emissions}}$$

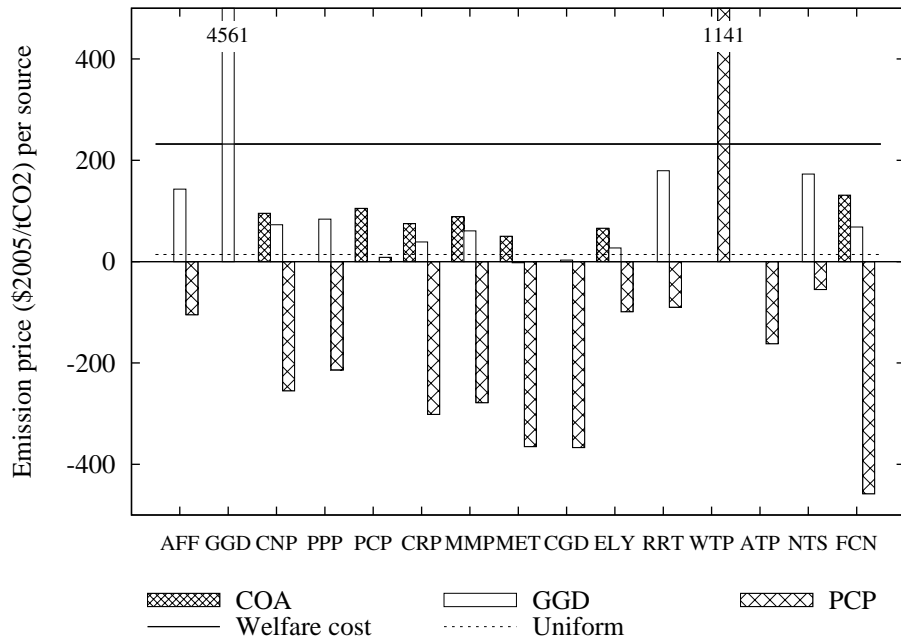
If leakage rates were uniform across sources, the structure of optimally differentiated carbon prices would not change compared with the domestic-centred policy. However, as shown in Figure 9, leakage rates do vary considerably across sources, with

<sup>16</sup>The model comparison study EMF 29 (summarised in Böhringer et al., 2012) covers different aspects of carbon leakage as well as measures designed to counteract it.

<sup>17</sup>Still, the only instrument available is domestic carbon prices, and domestic welfare remains the optimality criterion.

<sup>18</sup>For comparison purposes, Appendix A.2 shows the leakage rates in the situation with a uniform carbon price.

Figure 10: Optimal carbon prices with leakage



a range of between 0.3 and 1, except for one extreme outlier, namely GGD inputs into GGD production, where the leakage rate is almost -1.

Hence, starting from the domestically optimised carbon prices and targeting world emissions (at the level that results from the price pattern in Figure 2) induces price adjustments. These adjustments are downwards for sources that have above-average leakage rates, and vice versa.<sup>19</sup> The adjusted prices are shown in Figure 10. However, the quantitative differences with the initial scenario (Figure 2) in which leakage was disregarded, are small for most sources. As a rough pattern, the optimal carbon prices for COA increase slightly because leakage rates for coal are below average, whereas those for PCP decrease. The outlier in the leakage rates is an outlier in carbon prices as well; indeed, the carbon price for the source GGD in sector GGD increases dramatically.

<sup>19</sup>The average leakage value cannot be pinned down in a straightforward manner. Calculating average leakage would require changing all carbon prices at the same time. As these prices vary (with some even negative), a “uniform” variation cannot be defined without arbitrariness.

## 4 The role of excise taxes on fuels

It is clear that we must interpret the modelling results from Section 3 with great caution and avoid rushing into distilling real-world policy recommendations from them. As they stand, these results are explorative and primarily informative about the working mechanisms of models routinely used to evaluate climate policy.<sup>20</sup> As such they should be seen as an input into an iterative process of model adjustments and interpretation of model results that would ideally result in the critical revision of all model features that are drivers of the structure of optimally differentiated carbon prices.

Take, as an example, the output subsidy in WTP, which has emerged as the main reason for the disproportionately high optimal carbon prices in this sector. Before we may think of translating this result into policy advice, several rounds of checking are necessary. Are the subsidy rates in the GTAP data set reliable? Is there any particularity in the market structure of WTP that might explain this outlier in the data? What policy goal has led to the particularly high subsidy? Can this policy goal be interpreted as the correction of a market distortion, which then must be integrated into the model to ascertain a full picture?

Performing checks of this kind for all aspects of the model that have turned out to be drivers of the simulation results would require a large-scale interdisciplinary project. A huge number of experts would have to be involved in order to provide detailed knowledge on specific sectors such as WTP. Although such an effort is beyond the scope of the present paper, it does address one prominent example as a sensitivity analysis. This exemplifies how model development and modification could be driven by the results presented in Section 3.

For this analysis, I choose the case of pre-existing taxes on the use of transport fuels; these taxes trigger large compensatory subsidies on these fuels as an element of optimally differentiated carbon prices. An obvious caveat runs as follows. In the model, pre-existing taxes on fuels are modelled as pure distortions without any underlying rationale except for the generation of government revenue. In the real world,

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<sup>20</sup>Strictly speaking, I can only make claims about the model WorldScan. However, my guess is that other GTAP-based CGE models used to evaluate EU climate policy, such as PACE, GEM-E3, GEMINI-E3 and DART, would produce similar results.

however, different arguments are used to justify fuel excises on economic grounds: (1) internalisation of local environmental damage (air pollution), (2) internalisation of congestion externalities and (3) equivalence financing of road infrastructure (see, e.g., the discussion in Parry and Small, 2005). In all three cases, fuel excises are not a first-best instrument, but it might be argued that they are a reasonable substitute in a situation where a first-best instrument is not readily available.

The model set-up used for the simulations in this section is based on the third argument above.<sup>21</sup> The fuel excise tax on PCP is now modelled as a joint input into consumption and production. The underlying assumption is that each unit of fuel used requires, as a complement, the construction and repair of roads. The quantity of this joint input is determined by the level of the excise tax in the GTAP data set, and it is assumed to be produced by the NTS sector (which includes construction).<sup>22</sup>

The simulation results show the optimal pattern of differentiated carbon prices if fuel excise taxes are modelled as a joint input only in the transport sectors and in final consumption (Figure 11), or in all non-energy sectors (Figure 12).<sup>23</sup>

Figures 11 and 12 confirm our expectations on the grounds of the distortion argument. Once fuel excise taxes are no longer modelled as a pure distortion, no reason remains to neutralise them by means of negative carbon prices. The carbon prices of PCP use are now much more in line with those of other fuels, except for the sectors in which the fuel excise tax has not been replaced by a joint input.

## 5 Conclusions

Economic thought on climate policy as an instance of environmental regulation is strongly dominated by the principle of a uniform carbon price. In stylised mod-

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<sup>21</sup>The other two arguments are more difficult to model because they involve externalities. My guess, however, is that the consequences for the outcome would differ little. The only relevant aspect in the present context is that the fuel excise is no longer distortive regardless of the compensating mechanism.

<sup>22</sup>In order to keep the total output of the NTS sector unchanged with respect to the simulations in Section 3 I have introduced a compensatory input tax on NTS for all other uses than road construction work.

<sup>23</sup>The choice between the scenarios in Figures 11 and 12 would require an answer to the question of whether PCP inputs into non-transport sectors are actually fuels for transport services that have not been outsourced to the transport sector (as assumed in Figure 12). This cannot be resolved without extensive data work, if it can be resolved at all.

Figure 11: Optimal prices with the alternative modelling of excise taxes (1)

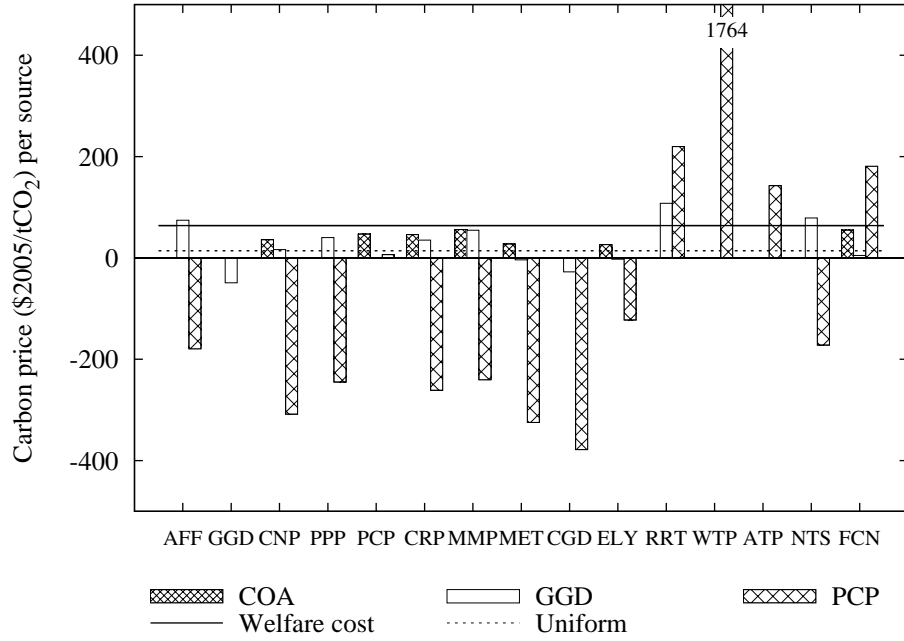
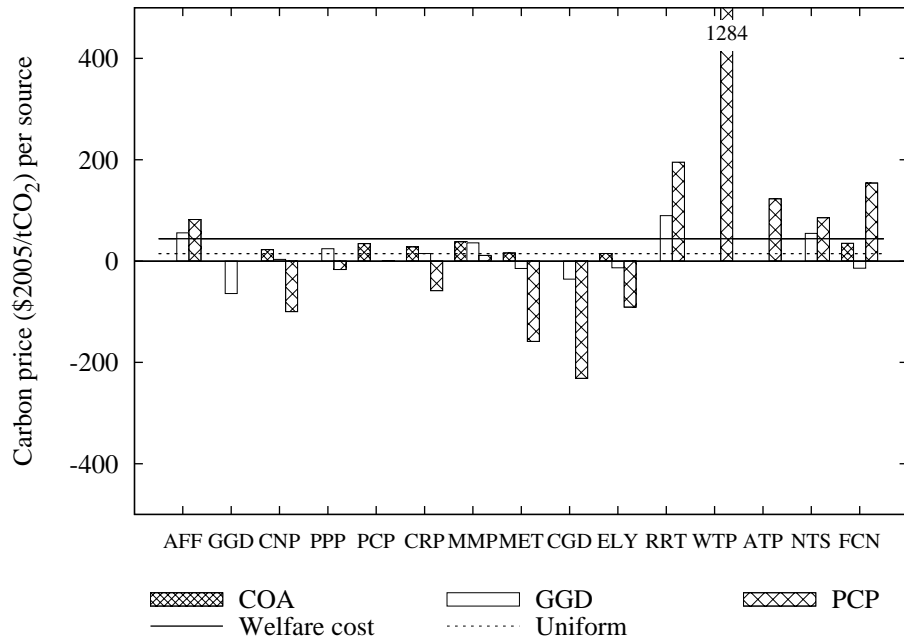


Figure 12: Optimal prices with the alternative modelling of excise taxes (2)





els that contain no further distortions, a uniform carbon price can be identified as the most appropriate instrument to equalise marginal abatement costs across sources. This approach inspires environmental economists to advocate emission trading schemes that have maximum scope, allowing for as much “where”, “what” and “when” flexibility as possible.

Economists realise that the principle of uniform carbon pricing breaks down in a “second-best” world with other pre-existing distortions such as taxes or market power in domestic and international markets.<sup>24</sup> Nevertheless, the predominating implicit assumption is that climate policy should not react to this by differentiating carbon prices by source. A single study (Böhringer et al., 2010) treats this assumption as hypothesis, which is tested using a CGE model and confirmed. However, the set-up of that study restricts carbon prices differentiation to two prices, one for the energy-intensive sectors and one for the rest of the economy.

By contrast, the simulations in the present paper show that uniform, or almost uniform, carbon prices are not the typical outcome of a standard CGE model when distortions through taxes and international trade are taken into account and separate treatment of all sources is allowed for. In this set-up, welfare-maximising differentiated carbon prices in an EU-only climate policy (reduction in CO<sub>2</sub> emissions by 20 % in 2020) in WorldScan can be characterised as follows:

- The optimal pattern of carbon prices is highly differentiated, ranging from almost prohibitive taxes to high subsidies (with a range of more than 1700 euros per ton of CO<sub>2</sub>).
- The welfare gain from switching from a uniform price to optimally differentiated prices is enormous, equivalent to a 27 % emission reduction for free.
- The most important drivers of carbon price differentiation are market power in export markets and taxes on consumption, intermediate inputs and domestic outputs.

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<sup>24</sup>However, the best-known discussion about the second-best characteristics of environmental levies (a possible “double dividend” from the interaction of environmental and labour market distortions; see Bovenberg (1999) for an overview) is not about the structure but rather about the level of taxes.

- By contrast, market power in import markets and other taxes (tariffs, taxes on investment and income) are less important.
- Accounting for carbon leakage to non-coalition regions leads to considerable shifts in the pattern of optimally differentiated prices, but it does not change the conclusion that differentiation is highly desirable.

It cannot be stressed enough that these *model results* are not necessarily real-world features. They must therefore not be misunderstood as implicit policy advice. However, they have been generated with a model that is, variations in a number of details notwithstanding, representative of the class of the CGE models routinely used to evaluate climate policy options. Therefore, the effects that drive the results in the present paper are likely also to co-determine the results of other CGE studies, even though they have not been focused upon before. The results thus confront economists that continuously apply these models to ever-varying versions of climate policy with the following questions: do we believe that pre-existing market distortions actually produce such a large variation in the pattern of optimally differentiated carbon prices? Or are we convinced that the principle of a uniform carbon price should remain an important driver of the results nevertheless?

The present paper only raises these questions, but cannot answer them. An encompassing answer would require a huge interdisciplinary effort, scrutinising each of the distortions present in the model. What the paper does show, however, is a possible approach if researchers are convinced that optimal carbon prices are not as diverse as implied in the model. Once we are prepared to view pre-existing taxes not as pure distortions, but as instruments that (partially) internalise externalities, this has direct consequences for the pattern of optimally differentiated carbon prices. For the concrete example of fossil fuel excises on intermediate inputs and consumption, the paper shows that modelling them as joint inputs (to be interpreted as road construction complementary to transport services), instead of taxes, eliminates the subsidy peaks in the pattern of optimally differentiated carbon prices.

While this revision of modelling pre-existing distortions is cumbersome, it is indispensable. The barrier to making carbon price differentiation an instrument of actual climate policy must be set at a high level. After all, carbon price differentiation is likely to bring high policy costs with it. The process of actually *determining* the

optimal pattern of differentiation would certainly attract lobby groups, each with their own model showing – surprise! – that the carbon price in their own sector must be particularly low. This is an undesirable situation, and thus the level of welfare gains required to justify entering a regime of this sort should be high. However, if the welfare gains to be reaped are even close to those calculated in the simulations of this paper, namely equivalent to a 27% emission reduction for free, this option should not be easily dismissed.

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# Appendices

## A.1 Sensitivity: different baseline assumptions

The simulations in an earlier version of this paper were based on a different set of baseline assumptions (see Table 6). After switching to the newer baseline (see Table 5) it turned out that the baseline assumptions have hardly any consequences for the pattern of optimally differentiated carbon prices (Figure 13; compare with Figure 2). In contrast to the structural modelling assumptions crucial for the model results (see Section 4), the baseline assumptions are thus of minor importance.

Table 6: Alternative baseline in 2020: Quantities and prices

Economic indicators	2020 value as a multiple of 2004	Yearly growth 2004-2020 (%)
Population	1.060	0.4
Real GDP	1.091	0.5
Fossil energy use	0.835	-1.1
Oil	0.827	-1.2
Natural gas	0.709	-2.1
Coal	1.032	0.2
Electricity use	1.344	1.9
CO <sub>2</sub> emissions	0.854	-1.0
Fossil energy intensity	0.756	-1.7
Emission intensity	1.023	0.1
Fossil energy prices		
Oil	2.338	5.5
Natural gas	2.370	5.5
Coal	1.376	2.0

## A.2 Leakage rates

The leakage rates shown in Figure 9 have been calculated based on optimally differentiated carbon prices. For comparison purposes, Figure 14 shows the leakage rates with a uniform carbon price. The general pattern is similar. However, with a uniform carbon price the spread among leakage rates is larger. For one source, PCP

Figure 13: Optimally differentiated emission prices (alternative baseline)

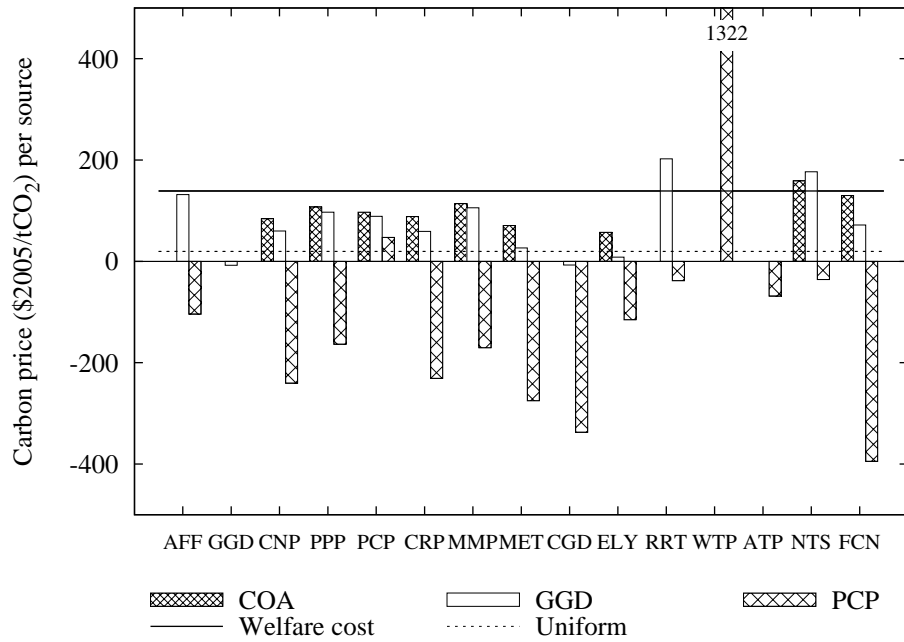
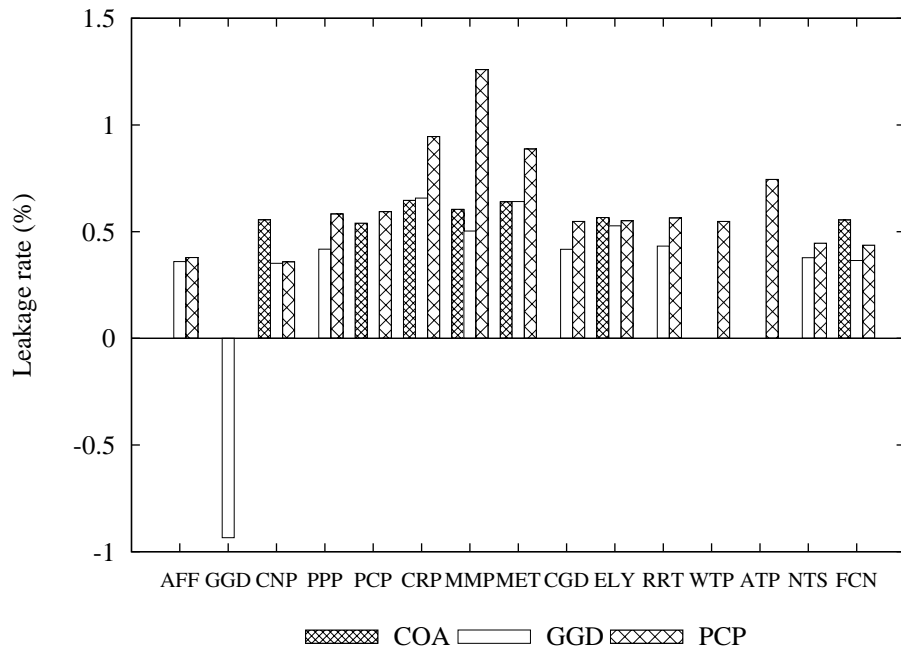


Figure 14: Leakage rates (uniform carbon price)



in MMP, leakage even exceeds 100%. Differentiating carbon prices apparently also leads to a reduction in the spread of leakage rates.