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Published in:
WORLD DEVELOPMENT

DOI:
[10.1016/j.worlddev.2019.104681](https://doi.org/10.1016/j.worlddev.2019.104681)

Published: 01/01/2020

Document Version
Peer reviewed version

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Please cite the original version:
Kuosmanen, T., Zhou, X., & Dai, S. (2020). How much climate policy has cost for OECD countries? *WORLD DEVELOPMENT*, 125, 1-8. [104681]. <https://doi.org/10.1016/j.worlddev.2019.104681>

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How much climate policy has cost for OECD countries?

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Abstract

High economic cost of climate policy has attracted critical debate since the Kyoto Protocol. However, reliable empirical evidence of the abatement cost of green-house gases across countries remains scant. In this study we estimate the average yearly green-house gas abatement costs per capita for a panel of 28 OECD countries in years 1990–2015. The marginal abatement costs are estimated using a novel data-driven approach based on convex quantile regression. Compared to traditional frontier estimation methods, the quantile approach takes into account a broader set of abatement options and is more robust to inefficiency, noise, and heteroscedasticity in empirical data. The comparison of OECD countries shows that the actual abatement cost per capita has been very modest, much lower than predicted in the late 1990s. This result has profound policy implications, calling for more ambitious climate change mitigation strategy in the future.

Keywords

Abatement cost; Climate change; Convex quantile regression; Green-house gases; Kyoto Protocol; OECD countries.

Manuscript accepted for publication in *World Development*, Vol. 125. The published article is available online at: <https://doi.org/10.1016/j.worlddev.2019.104681>

1. Introduction

Global climate change, attributed to the increased levels of green-house gases (GHG) (particularly carbon dioxide, CO₂)¹ produced by the use of fossil fuels, is nowadays widely recognized as the most the most pressing challenge of our time (e.g., Cifci and Oliver, 2018). Increasing concentration of GHG in the atmosphere contributes to global warming, which already contributes to increasing frequency and intensity of extreme weather events around the world (e.g., IPCC, 2018). Mitigation of climate change has proved extremely challenging due to distributional and equity concerns across different countries and generations (e.g., Markandya, 2011; Mattoo and Subramanian, 2012), involving both tradeoffs and synergies with other development goals (Halsnæs et al., 2011). In the future, global warming and more severe weather events are expected to cause severe loss of eco-systems and human life as well as inflict damage to property. Poorest countries and regions that have no resources for climate change adaptation are likely to suffer disproportionately larger damage costs (e.g., Abeygunawardena et al., 2009)

International treaties to mitigate climate change date back to the early 1990s. The United Nations Framework Convention on Climate Change (UNFCCC) was opened for signature in Rio de Janeiro in 1992, and has been subsequently ratified by all member states of the United Nations. Five years later in 1997, a group of 43 industrialized countries signed a more ambitious treaty known as the Kyoto Protocol where the signatory countries committed themselves to binding GHG emission reduction targets. Although the USA later declined to ratify the treaty, and Canada unilaterally withdrew from the treaty after the ratification, the Kyoto Protocol came into effect in 2005. The first commitment period was completed in 2008-2012, and the second commitment

¹ The Kyoto Protocol recognizes four greenhouse gases [carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulphur hexafluoride (SF₆)] and two groups of gases [hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)]. The GHGs are converted into CO₂ equivalents based on their global warming potential.

period (known as the Doha Amendment) takes place in 2013-2020. Parties to the UNFCCC continue to meet on a regular basis to discuss climate policy beyond 2020. In contrast to the binding targets of the Kyoto Protocol, the Paris Agreement in 2016 requires the signatory parties to put forward their “best efforts” through nationally determined contributions.

In the late 1990s, the economic cost of Kyoto Protocol was intensively debated both in academic and political arenas. A seminal study by Nordhaus and Boyer (1999) applies integrated assessment model (IAM) to estimate the global cost of the Kyoto Protocol. According to their estimates, the net present value of total cost is \$716 billion US dollars (prices of 1990), of which the share of the USA would be almost two thirds. They also argue that the Kyoto Protocol is highly cost-ineffective with the total cost 7 times higher than the benefit. Citing estimates from other sources, Murkowski (2000) argues that the average cost for a US household could be as high as \$2,728 per year, leading to eradication of 2.4 million jobs. The perceived high cost on the US economy has been the most important single reason for the USA’s withdrawal from the Kyoto Protocol and later the Paris Agreement.

As the second commitment period of the Kyoto Protocol draws to its end in 2020, it is high time to shed empirical light on the cost of Kyoto, and climate policy in general. However, empirical evidence concerning the cost of Kyoto remains scant (see Cifci and Oliver, 2018, and references therein). Indeed, empirical cost assessment of climate policy involves many severe challenges. Firstly, specifying a meaningful counterfactual to the Kyoto Protocol is far from self-evident. As noted above, several countries that signed the Kyoto Protocol have later unilaterally withdrawn from their commitments or simply failed to comply with their targets. On the other hand, countries that did not commit to the Kyoto targets have also implemented voluntarily abatement measures. Secondly, leakage of emissions through trade to developing countries with lower emissions

standards is a well-recognized problem. Thirdly, there are indirect costs and benefits that are difficult to measure. For example, measures to abate CO₂ may also lead to reduction in PM and SO_x emissions, improving the air quality at local or regional levels.

The purpose of this study is to address the first challenge by estimating the economic cost of the *actual change* of GHG emissions relative to 1990, the benchmark year of the Kyoto Protocol. To estimate the marginal abatement cost, we resort to *convex quantile regression* (Banker et al., 1988; Wang et al., 2014; Kuosmanen et al., 2015; and Kuosmanen and Zhou, 2018), which is a data-driven estimation method that combines the key advantages of convex nonparametric regression (Hildreth, 1954; Kuosmanen, 2008) and quantile regression (Koenker and Basset, 1978; Koenker, 2005). The main appeal of convex regression is that it draws its power from standard axioms of economic theory such as monotonicity and convexity, and does not depend on any arbitrary functional form assumptions. The key advantage of using quantiles is that impacts of inefficiency, stochastic noise, and heteroscedasticity in empirical data are explicitly modeled without any restrictive prior assumptions (Kuosmanen and Zhou, 2018). Further, our estimation of marginal abatement cost takes into account a broader set of abatement options than most previous studies.

The main contribution of this paper is to shed new empirical light on the cost of climate policy among the signatory countries of the Kyoto Protocol. Using an international panel data of OECD countries, we estimate the average yearly abatement costs of GHG per capita in 1990-2015. We find that the abatement costs in the EU countries range from €2 to €112 per capita per year, whereas in the non-European OECD countries, the increase in GHG emissions yielded benefits ranging between €2 - €76 per capita per year. Considering the difference between the highest cost of GHG abatement and the highest benefit of increasing GHG emissions among the OECD

countries as an upper bound for the economic cost of climate policy, the yearly abatement cost per capita seems a relatively modest burden for the wealthy OECD economies. In light of our empirical results, the forecasted costs of the Kyoto Protocol from the 1990s appear rather pessimistic: the industrialized countries could clearly afford to pursue more ambitious climate change mitigation in the future.

The rest of the paper is organized as follows. Section 2 presents a brief literature review on the economic cost of the Kyoto Protocol, focusing on the macro-level studies. Section 3 introduces our empirical estimation strategy based on convex quantile regression. Section 4 describes the data sources and variable specification. Empirical results are reported in Section 5. Concluding remarks and policy implications are discussed in Section 6. Additional tables and figures illustrating the empirical application are presented in the Appendix.

2. Cost of Kyoto Protocol: brief literature review

The economic cost of climate policy attracted considerable attention in the academic literature in the aftermath of the Kyoto Protocol in the late 1990s and early 2000s. The main attention of this literature is in *ex ante* forecasting of the potential cost of climate policy in different policy scenarios. According to the methodological survey by Zhang and Folmer (1998), the most commonly used approaches include integrated assessment models (IAM), computational general equilibrium (CGE) models, dynamic optimization, macroeconomic modeling, input-output models, and hybrid models that combine some elements of two or more approaches.

While the scientific community has a broad consensus about the causal effect of GHG on global warming and the necessity to abate GHG to mitigate the damage (e.g., IPCC, 2018), there is no consensus about the economic cost of GHG abatement. Published forecasts of the economic

costs of reducing the GHG emissions to meet the Kyoto targets exhibit very large variation of factor 5 or higher (e.g., Weyant and Hill, 1999; Fischer and Morgenstern, 2006). The large differences in forecasts arise due to multiple factors, such as the projections of the base line emissions, the policy scenarios considered, the degree of flexibility allowed in meeting the targets, structural characteristics and assumptions of the models, and the valuation of ancillary benefits (see Fischer and Morgenstern, 2006, for further discussion).

A highly influential stream of studies on the economic cost of the Kyoto Protocol was presented at the Stanford Energy Modeling Forum (EMF) (Campbell Watkins, 1999). Subsequently, 14 EMF studies were published in a special issue of *The Energy Journal* (see Weyant and Hill, 1999, for an introduction and overview). Table 1 summarizes the range of EMF estimates published in 1999 by presenting the minimum and maximum value of the predicted loss of GDP per capita in year 2010 in the “No trading” policy scenario that appears to best describe the actual situation in 2010.

Table 1: The range of EMF estimates for the predicted loss of GDP per capita in year 2010 in the “No trading” scenario (€²⁰¹⁰ per capita)

Region	min	max
USA	155	742
EU	130	708
Japan	99	811
Canada-Australia-New Zealand	167	729

For the sake of comparability, in Table 1 we have adjusted the minimum and maximum value of the 8 EMF forecasts reported in Weyant and Hill (1999) from US dollars of year 1990 to euros of year 2010 (the base year used in our empirical analysis in Section 5), and divided the total

cost by the total population of the region in year 2010 (see Section 4 for the presentation of data sources). The minimum and maximum values of the EMF forecasts illustrate the large spread in the expert forecasts for all regions, with the largest variation found in the case of Japan where the range of forecasts is from the minimum of €99 per person up to €811 per person in year 2010.

Inspired by the EMF studies, a number of subsequent papers continued to examine the cost of Kyoto Protocol for different regions or countries using different approaches (e.g., Böhringer and Vogt, 2003; Viguier et al., 2003; McKibbin and Wilcoxon, 2004; Dagoumas et al., 2006; Klepper and Peterson, 2006; Simões et al., 2008; Markandya et al., 2015).² Subsequent studies have also tried to explain the variability in cost estimates based on meta-analysis (e.g., Fischer and Morgenstern, 2006). Unfortunately, since professional economists consider alternative policy scenarios and recognize various sources of uncertainty related to forecasts, the policy discussion is often dominated by think tanks and lobbyists who do not hesitate to state an exact price tag based on some *ad hoc* model. Typically such price tags are based on wild, unrealistic assumptions, and are grossly exaggerated.

Given the large volume of *ex ante* forecasts both in academic literature and popular media, however, surprising little attention has been paid to *ex post* empirical analysis of the economic impact of the Kyoto Protocol and climate policy more generally. One notable exception is the recent study by Cifci and Oliver (2018) that employs differences-in-differences estimation to investigate the causal effect of the Kyoto Protocol on country-level GHG emissions and economic growth, taking the signatory countries (i.e., Annex I) as the treatment group. However, this specification of the treatment group seems questionable as some key countries that signed the

² A large volume of studies consider micro-level impacts on individual establishments, sectors, industries, or regions. For the sake of compactness, this section focuses on macro-level studies at the national or global levels.

Kyoto Protocol failed to ratify it (USA), subsequently withdrew from it (Canada), or simply failed to meet their targets. Further, Annex I countries of the Kyoto Protocol include all major industrialized countries of the late 1990s, and hence the selection to treatment is clearly not random, which may cause severe bias in the estimation and statistical tests. Clearly, further empirical evidence regarding the economic cost of climate policy is needed.

3. Marginal abatement cost approach

In this study we estimate the total abatement cost (AC) of green-house gas emissions (GHG) by multiplying the actual yearly change in GHG by its marginal abatement cost (MAC). Specifically, the abatement cost in country i in year t is calculated as

$$AC_{it} = (GHG_{it} - GHG_{i,t-1}) \cdot (MAC_{it} + MAC_{i,t-1})/2. \quad (1)$$

This estimate is based on the assumption that the change in GHG emissions is so small that the average MAC estimated using input-output quantities in years $t-1$ and t provides a good approximation of the opportunity cost of abatement. Empirically, the yearly changes in GHG are indeed rather small compared to the total yearly emissions of GHG: in the sample of 28 OECD countries in years 1990-2015 introduced in the next section, the median yearly change in GHG emissions was 2.4% of the total GHG emissions, and the average yearly change was 3.3%.

The combined use of the actual data of GHG reductions and their MAC for economic valuation of climate policy effectively circumvents the need to assume some hypothetical counterfactual alternative for the Kyoto Protocol. We do not need to specify in advance whether a country committed to Kyoto targets, complied with the targets, or just relied on voluntary abatement efforts. On the other hand, we must recognize that this approach does not take into account possible leakage of emissions through trade or ancillary benefits associated with improved

local air quality.

Following Kuosmanen and Zhou (2018), marginal abatement cost is defined as the least cost alternative to reduce emissions either through increase in input use or downscaling activity, specifically

$$MAC_{it} = \min\{MRT(y_{it}, b_{it}), MP(K_{it}, b_{it}), w_{it}MP(L_{it}, b_{it})\}, \quad (2)$$

where y is the economic output (value added), b is the bad output (here GHG emissions), MRT is the marginal rate of transformation between the good and bad outputs, K and L are the capital and labor inputs, respectively, MP is the marginal product of input on bad output, and w is the average wage rate. Kuosmanen and Zhou (2018) argue that the conventional estimates published in the frontier estimation literature tend to focus solely on downscaling (i.e., the MRT component in (2)) as the only abatement strategy, which will systematically overestimate MAC . They find that considering the input side abatement options (i.e., the MP components in (2)) such as fuel switch or investment in cleaner technology substantially decreases the MAC estimates of the US electric power plants.

To estimate the marginal products and marginal rates of transformation, the conventional frontier estimation techniques also ignore impacts of inefficiency and noise (see Kuosmanen and Zhou, 2018, for further discussion). Clearly, the shadow prices on the frontier overestimate the shadow prices for inefficient producers. For example, the marginal abatement cost of CO_2 in a rich country such as Sweden that has already invested in CO_2 abatement should be considerably higher than the marginal abatement cost in a developing country such as China where considerable efficiency improvement potential still remains. Therefore, it would be misleading to assume that empirical estimates of MAC using Swedish data are directly applicable to China. Unfortunately, such a strong assumption is implicitly made whenever one applies MAC estimates that are based

on the efficient frontier to inefficient countries (or plants, firms, industries).

To take inefficiency and noise in data explicitly into account in the MAC estimation, Kuosmanen and Zhou (2018) resort to convex quantile regression. This method allows one to estimate the shadow prices locally at the given level of productive performance. The method is fully nonparametric: no restrictive functional form or distributional assumptions are required. The power of this method draws from the global shape constraints, in particular, monotonicity and convexity. At the aggregate level of countries, we consider it important to compare performance of countries relative to the constant returns to scale benchmark technology.

Consider the general econometric model of frontier production function (e.g., Kuosmanen and Kortelainen, 2012)

$$y_{it} = f(K_{it}, L_{it}, b_{it}) \cdot \exp(v_{it} - u_{it}), \quad (3)$$

where f is a non-parametric frontier production function, v_{it} is a random noise term with zero mean, and u_{it} a non-negative inefficiency term. In this specification, b is treated similar to inputs K and L , while in fact it is an undesirable output. However, we can interpret function f as the directional distance function with a specific direction vector that defines the boundary of the production possibility set (cf. Kuosmanen and Johnson, 2017). In practice, this conceptual distinction has no effect on empirical estimation.

It is important to stress that the MRT between good output y and bad output b depends on the realization of the random variables v_{it} and u_{it} . To see this, we differentiate y with respect to b to obtain

$$\frac{\partial y_{it}}{\partial b_{it}} = \frac{\partial f(K_{it}, L_{it}, b_{it})}{\partial b_{it}} \cdot \exp(v_{it} - u_{it}). \quad (4)$$

The partial derivate on the left-hand side of (4) defines the MRT between the good and bad outputs

(i.e., the first component on the right-hand side of (2)), whereas the partial derivative on the right-hand side of (4) indicates the marginal effect of b on the efficient output on the frontier. Clearly, as inefficiency u increases, *ceteris paribus*, the MRT between good and bad outputs decreases. Therefore, the MAC of the bad output b is a decreasing function of inefficiency u .

In contrast to the conventional frontier estimation approaches, in convex quantile regression we do not estimate the frontier f explicitly, but rather, we estimate the shadow prices that characterize the MRT and MP conditional on the realizations of v_{it} and u_{it} . Following Kuosmanen and Zhou (2018), we estimate the shadow prices $\beta_{it}^K, \beta_{it}^L, \beta_{it}^b$ of capital, labor, and GHG, respectively, by solving the following nonlinear programming (NLP) problem for the following 10 quantiles $\tau = (0.05, 0.15, 0.25, \dots, 0.85, 0.95)$:³

$$\begin{aligned}
& \min_{\beta, \varepsilon^-, \varepsilon^+} (1-\tau) \sum_{t=1}^T \sum_{i=1}^n (\varepsilon_{it}^-)^2 + \tau \sum_{t=1}^T \sum_{i=1}^n (\varepsilon_{it}^+)^2 \\
& \text{subject to} \\
& \ln y_{it} = \ln \gamma_{it} - \varepsilon_{it}^- + \varepsilon_{it}^+ \quad \forall i, \forall t \\
& \gamma_{it} = \beta_{it}^K K_{it} + \beta_{it}^L L_{it} + \beta_{it}^b b_{it} \quad \forall i, \forall t \\
& \gamma_{it} \leq \beta_{js}^K K_{it} + \beta_{js}^L L_{it} + \beta_{js}^b b_{it} \quad \forall i, j, \forall t, s \\
& \beta_{it}^K \geq 0, \beta_{it}^L \geq 0, \beta_{it}^b \geq 0 \quad \forall i, \forall t \\
& \varepsilon_{it}^- \geq 0, \varepsilon_{it}^+ \geq 0 \quad \forall i, \forall t
\end{aligned} \tag{5}$$

The optimal solution to problem (5) indicates the predicted output γ_{it} for country i in year t at the performance level τ such that $100 \cdot \tau$ % of observations fall below that performance level. Non-negative variables ε_{it}^- and ε_{it}^+ capture negative and positive deviations from the quantile frontier. While ε_{it}^- and ε_{it}^+ capture inefficiency u and noise v , in this study we do not try to identify or isolate these sources of deviations more explicitly as our focus is on the marginal properties

³ In the empirical part of this paper, we used GAMS software with KNITRO solver for computing the optimal solutions to the NLP problem (5).

$$\beta_{it}^K, \beta_{it}^L, \beta_{it}^b.$$

Recall that problem (5) is solved 10 times for different levels of τ , and hence we obtain 10 different sets of shadow prices for each country and year; the resulting output and input isoquant maps are illustrated in Figures A1 and A2 in Appendix. We estimate the MAC using the weighted average of $\beta_{it}^K, \beta_{it}^L, \beta_{it}^b$ coefficients of the two quantiles nearest to the observed data point, except for those observations that fall below quantile $\tau = 0.05$ or above quantile $\tau = 0.95$, for which the shadow prices of the nearest quantile are used. See Kuosmanen and Zhou (2018) for more detailed discussion of the estimation procedure. We here deviate from Kuosmanen and Zhou (2018) in that the composite error term is modeled in a multiplicative rather than additive form, and that the quantile frontiers are enforced to exhibit constant returns to scale.

4. Data and variables

We empirically estimate the abatement cost of GHG at country level based on a yearly panel data of 28 OECD countries during the period 1990-2015. The countries included in this study are listed in Tables 2 and 3 below, while the rest of OECD countries had to be excluded due to insufficient data.⁴ The input-output variables of the production model are specified as follows (the variable code used by the OECD stated in parentheses):

- Output y : value added (VALK), billion €²⁰¹⁰.
- Bad output GHG : total GHG emissions excluding land use, land use change and forestry, million tons of CO₂ equivalents.
- Capital input K : net capital stock (CPNK) (in billion €²⁰¹⁰).

⁴ The following OECD countries had to be excluded due to missing data of the capital input in the OECD STAN database: Chile, Costa Rica, Lithuania, Portugal, Spain, Switzerland, and Turkey. In addition, Japan and Mexico were excluded due to missing data of labor input.

- Labor input L : hours worked by total engaged (HRSN) (billion hours).

In addition to the input and output variables required for estimating the shadow prices using NLP formulation (5), the following variables are needed for estimating the MAC and the abatement cost per capita:

- Wage rate W : ratio of labor costs (LABR) to hours worked (HRSN) ($\text{€}^{2010}/\text{h}$).
- Population (all ages, number of persons).

All variables are public data obtained from the OECD database.⁵ All monetary variables expressed in other currencies were converted to Euro using historical currency conversion rates.⁶ Since the wage rate W is not directly available in the OECD database, we use the ratio of labor costs to labor hours as the measure of average wage rate. The production data are based on the national accounts of the OECD member states, and are reported as part of the OECD Structural Analysis (STAN) database. The data of GHG emissions are based on the UNFCCC statistics and replies to the OECD State of the Environment Questionnaire. For descriptive statistics of the input and output variables, see Table A1 in the Appendix.

5. Results

5.1 Marginal abatement cost estimates

Since our purpose is to evaluate the cost of climate policy based on the actual observed change in the GHG emissions weighted by the marginal abatement cost, our results critically depend on our estimated MAC. Therefore, we first present our MAC estimates before proceeding to our empirical estimates of abatement cost per capita across countries.

⁵ OECD Stat: <https://stats.oecd.org>

⁶ Historical Currency Converter: <http://www.historicalstatistics.org/Currencyconverter.html>

Table 2 summarizes our marginal abatement cost estimates across countries by presenting the average MAC in € per metric ton over the time period 1990-2015 (the interquartile range of MAC is presented in parentheses).⁷ In this table, the OECD countries are classified into four groups: the old EU-15 member states since 1995, the transition economies of Eastern Europe that are currently EU members, EFTA countries, and the non-European OECD countries. In each group, countries are ranked in descending order of the average MAC. Note that all OECD countries listed in Table 2 are Annex I signatory parties to the Kyoto Protocol, except for Israel and South Korea. The EU transition economies are included in Annex I, but not in Annex II classification. All EU-15 and EFTA countries as well as non-European OECD countries except for Israel and South Korea are Annex II parties to the Kyoto Protocol, which have agreed to provide financial and technical support to developing countries to assist them in both mitigation of and adaptation to climate change.

Among the EU-15 countries, the marginal abatement costs vary from €182 per ton in Austria up to €507 per ton in Sweden. The range of marginal abatement costs in the EFTA countries and in the non-European OECD countries does not differ dramatically from that of the EU-15 countries. In the transition economies of Eastern Europe, however, the marginal abatement costs are notably lower, ranging from €116 per ton in Slovakia to €189 per ton in Estonia. The marginal abatement cost reflects the carbon intensity of the economy. A country with a large service sector compared to manufacturing can produce value added with relatively low GHG emissions (consider, e.g., Luxembourg, a major financial center in Europe). Former socialist economies of the Eastern Europe have lower MAC due to relatively inefficient use of resources

⁷ The interquartile range is a measure of statistical dispersion, defined as the difference between the 3rd and the 1st quartile, or equivalently the 75th and the 25th percentiles of the distribution.

especially during the first years of their transition towards the EU market in the 1990s.

Table 2: Marginal abatement cost by country ($\text{€}^{2010} / \text{ton}$), average of 1990-2015 (interquartile range in parenthesis).

EU-15 (Annex II)			EU transition economies (Annex I)		
Sweden	507	(207)	Estonia	189	(116)
Luxembourg	431	(64)	Slovenia	189	(71)
United Kingdom	421	(50)	Poland	129	(43)
Ireland	406	(11)	Hungary	121	(34)
Italy	349	(103)	Latvia	119	(16)
Belgium	340	(69)	Czech Republic	119	(43)
Greece	324	(59)	Slovakia	116	(43)
Netherlands	309	(94)			
Germany	289	(71)	Non-European OECD		
France	289	(181)	Canada	404	(1)
Finland	268	(112)	Israel*	396	(1)
Denmark	262	(190)	United States	318	(59)
Austria	182	(13)	Australia	311	(17)
			New Zealand	300	(69)
			South Korea*	217	(14)
EFTA (Annex II)					
Norway	435	(82)			
Iceland	198	(57)			

* Non-Annex I countries. All other countries are listed in Annex I of the Kyoto Protocol.

The interquartile range presented in parentheses is a measure of statistical dispersion of the MAC estimates. For Canada and Israel the MAC is virtually constant throughout 1990-2015, whereas for the EU-15 countries, most notably Sweden, France, and Denmark, the interquartile range of MAC is rather high. This is mainly due to the sharp increase of MAC during this time period.

While environmental performance of countries relative to quantile frontiers is not the main focus of this paper, it is worth to note in passing that Canada, Luxembourg, Norway, and the UK

rank consistently among the best performing countries throughout the time period, whereas the Czech Republic, Latvia and Slovakia rank consistently among the least productive countries. Most impressive performance improvement over the time period was shown by Denmark, France, the Netherlands, and Poland, whereas the relative performance of Estonia, Greece, Italy, and South Korea declined during this time period. See Table A2 in Appendix for a more detailed performance comparison of countries relative to the quantiles.

The country-level estimates reported in Table 2 are of similar order of magnitude as the MAC estimates reported in the frontier estimation literature (e.g., Lee and Wang, 2019), and those obtained by CGE models (e.g., Böhringer and Vogt, 2003; Viguier et al., 2003), but are considerably higher than the market prices of CO₂ allowances. According to Kuosmanen and Zhou (2018), the prices of CO₂ allowances fluctuated within the range of €5-€15 per ton in the European Union Emission Trading Scheme (EU ETS) in years 2014-2018. They note that the price range of CO₂ allowances is similar in Chinese ETS pilots as well as in California ETS. For comparison, Rubin et al. (2015) compare the cost of CO₂ capture and storage for coal plants, suggesting the price range of \$46-\$99 US per ton for post-combustion CO₂ capture at supercritical pulverized coal, and \$53-\$137 US per ton for coal-based integrated gasification combined cycle. In light of the market prices of CO₂ allowances and the cost of CO₂ capture and storage, the macro-level estimates reported in Table 2 seem relatively high. However, applying conventional shadow pricing methods (such as data envelopment analysis) to this data would yield even higher estimates of MAC (see Kuosmanen and Zhou, 2018, for further discussion).

Finally, large variance in the marginal abatement costs across countries suggests that the implementation of climate policy has been cost inefficient, even if one only considers the 28 OECD countries included in our sample data and completely ignores non-OECD countries. Note that

efficient allocation of GHG abatement across countries would require that the marginal abatement cost is the same in all countries; transfer payments could be used for sharing the resulting cost. For example, it would be cost efficient for most EU-15 countries to pay for GHG abatement in the EU transition economies or in non-Annex I parties of the Kyoto Protocol rather than implement expensive abatement in their own country. There does exist policy instruments such as the EU ETS mentioned above, where firms from different EU countries can buy and sell CO₂ emission allowances in order to achieve efficient allocation of abatement.⁸ However, the large variance in the average abatement costs across countries, even within the EU, suggests that allocation of GHG abatement across countries despite the EU ETS market has been far from cost efficient.

5.2 Abatement cost per capita

While the marginal abatement cost estimates are very interesting and relevant as such, the main objective of the present paper is to evaluate the cost of climate policy *ex post* in terms of the abatement cost per capita. To this end, Table 3 reports the main results of this paper: the average yearly abatement cost per capita for the sample of OECD countries during the period 1990-2015 (the interquartile range is presented in parentheses). As in Table 2, the countries are classified in four groups, and sorted within each group according to the abatement cost per capita from largest to smallest. Positive values reflect the magnitude of economic burden due to reduction of GHG emissions, whereas negative values can be interpreted as the economic benefit derived from increase in GHG emissions relative to the 1990 level, the benchmark year in the Kyoto Protocol.

⁸ Other policy instruments within the Kyoto Protocol include the Clean Development Mechanism and Joint Implementation, which allow signatory countries of the Kyoto Protocol abate GHG in developing countries.

Table 3: Abatement cost per capita per year (€^{2010} / person), average of 1990-2015 (interquartile range in parenthesis).

EU-15 (Annex II)			EU transition economies (Annex I)		
Luxembourg	112	(874)	Czech Republic	30	(75)
United Kingdom	83	(150)	Slovakia	15	(58)
Denmark	67	(293)	Hungary	15	(29)
Sweden	57	(165)	Poland	12	(40)
Germany	48	(107)	Slovenia	11	(53)
Finland	48	(345)	Estonia	3	(191)
Belgium	42	(169)	Latvia	3	(53)
Netherlands	23	(115)			
France	22	(73)	Non-European OECD		
Italy	14	(97)	United States	-9	(178)
Austria	2	(105)	Israel*	-30	(31)
Greece	-2	(161)	New Zealand	-48	(164)
Ireland	-8	(219)	Canada	-61	(296)
			South Korea*	-75	(122)
EFTA (Annex II)			Australia	-76	(101)
Norway	-6	(175)			
Iceland	-36	(101)			

* Non-Annex I countries. All other non-European countries are Annex II parties of the Kyoto Protocol.

Several interesting observations are worth noting in Table 3. First, the signs of the abatement cost estimates match well the climate policy commitments of countries. The abatement cost is positive for all EU countries (both EU-15 and the transition economies), except for Greece and Ireland. Furthermore, the abatement costs per capita in the transition economies of Eastern Europe were at the lower end of the range compared to the EU-15 countries, with the notable exception of the Czech Republic. In contrast, the EFTA countries in Europe and all non-European OECD countries have a negative abatement cost, which means that these economies have benefited from an increase in their GHG emissions.

Second, the magnitudes of costs (and benefits) prove modest compared to the EMF cost

forecasts published prior to the implementation of the Kyoto Protocol; compare with Table 1. The average annual abatement cost ranges from rather negligible €2 per capita in Austria up to €112 per capita in Luxembourg. In contrast, the average annual benefits from the increase in GHG emissions range from €2 per capita in Greece to €76 per capita in Australia. Note that zero level is not necessarily a correct benchmark to evaluate the cost of climate policy in the EU countries because the GHG emissions would have likely increased in the absence of the Kyoto Protocol. The benefits of GHG increase in the non-European OECD economies such as Canada or Australia might be a more appropriate counterfactual for the EU countries. In any case, the difference between the highest cost and the highest benefit among all OECD countries has been less than €200 per capita per year. For the wealthy OECD countries, this amounts to somewhere between 0.2-1.6 percent of the average yearly income, which is a very modest cost irrespective of whatever benchmark or counterfactual one might be using in the evaluation.

Third, the distribution of abatement cost across countries is very interesting. Among the EU countries, the allocation of the abatement targets across member states has been a political process, where the rich countries of Northern Europe were expected to bear a higher share of the cost than the Southern Europe or the new member states of Eastern Europe: the EU-15 had the overall target to cut GHG emissions by 8% from the 1990 levels, but within this overall target, each EU-15 member state had a differentiated reduction target. Results of Table 3 confirm with the differentiated targets, but also suggest that some EU-15 countries have paid a considerably higher price for climate policy than others. For example, our results indicate that the UK has paid a notably higher abatement cost per capita than all other EU countries (except for Luxembourg). This might be one of the contributing factors to the growing negative sentiment on the EU in the UK during the time period of our study, which eventually led to the Brexit vote in 2016.

Among the non-European OECD countries, it is well-known that the USA did not ratify the Kyoto Protocol. Canada initially ratified the Kyoto Protocol but later withdrew from it. Australia initially negotiated an easier target allowing it to increase its GHG emissions by 8% relative to the 1990 level, but did not ratify the treaty until the end of 2007. Interestingly, both Canada or Australia increased their GHG emissions more than the USA, which contributed to their economic growth with the average yearly benefits of €61 (Canada) and €76 (Australia) per capita, in contrast to the benefit of €9 per capita in the USA.

It is important to stress that the cost of GHG reduction cannot be attributed to climate policy alone because the business cycle and structural changes of the economy also contribute to the reduction of GHG emissions. As China and other developing countries have increased their global share of manufacturing output, the share of service sector has increased in almost all OECD countries. The financial crisis of 2007-2008 further accelerated the structural change, contributing to the decrease in GHG emissions in the OECD economies: the total GHG emissions of the sample of 28 OECD countries decreased by 8 percent from year 2007 to 2009. Despite a relatively large variance in cost of GHG abatement across countries and over time, the empirical comparison of the EU-15 countries that complied with the Kyoto targets and the heterogeneous group of non-European OECD countries provides at least a useful ballpark estimate of the economic cost of climate policy.

Finally, it is worth to stress that we have compared the cost of yearly changes in GHG emissions since 1990, which is the benchmark agreed upon by the signatory countries of the Kyoto Protocol.⁹ From the point of view of equity, taking 1990 as the benchmark is obviously a

⁹ The following five transition countries have a different base year: Bulgaria (1988), Hungary (the average of 1985-1987), Poland (1988), Romania (1989), and Slovenia (1986).

completely arbitrary political choice since most OECD countries have historically benefited from free emission of GHG to the atmosphere since the Industrial revolution (see, e.g., Markandya, 2011, Mattoo and Subramanian, 2012; for critical discussion). While Table 3 focuses on comparing the economic cost of *changes* in GHG emissions over time relative to their 1990 benchmark level, it is also interesting to compare the GHG intensity across the OECD countries.

Table 4: Carbon productivity (GDP / GHG) relative to that of Sweden, the average of 2010-2015.

EU-15		EU transition economies	
Sweden	100 %	Slovenia	33 %
Denmark	76 %	Latvia	30 %
France	75 %	Slovak Republic	29 %
Austria	66 %	Hungary	28 %
Luxembourg	60 %	Czech Republic	22 %
Ireland	60 %	Poland	17 %
Italy	60 %	Estonia	14 %
United Kingdom	59 %		
Netherlands	57 %	Non-European OECD	
Belgium	54 %	New Zealand	44 %
Germany	52 %	Israel*	43 %
Finland	50 %	Australia	36 %
Greece	32 %	United States	33 %
		Canada	33 %
		South Korea*	27 %
EFTA			
Norway	98 %		
Iceland	41 %		

* Non-Annex I countries. All other non-European countries are Annex II parties of the Kyoto Protocol.

Table 4 adds further perspective to our empirical results by presenting the relative carbon productivity across OECD countries in comparison to Sweden in years 2010-2015, the final five-year period in our study. Analogous to the conventional labor productivity and other partial

productivity indicators, we measure carbon productivity as the ratio of GDP to the total GHG emissions. To make the resulting ratios easier to compare, we normalize the carbon productivity ratios as percentages relative the most carbon productive country during this period, which is Sweden. Importantly, the relative carbon productivity indicators presented in Table 4 are simply calculated from the data, and as such, provide further perspective to our estimation results based on convex quantile regression.

The percentages reported in Table 4 indicate the efficiency of utilizing fossil fuels to generate economic output. For example, one ton of GHG emissions in Sweden generated on average three times higher economic output than one ton of GHG emissions in the USA or Canada. Recall from Table 2 that Sweden had also the highest marginal abatement cost of GHG among these 28 OECD countries.

The relative carbon productivity percentages reported in Table 4 reveal very large variation across OECD countries, which would suggest that there is considerable room for improving carbon productivity. While the high carbon productivity levels of Sweden and Norway may be a too ambitious benchmark for most other countries, at least in the short run, the comparison of the four groups of countries clearly reveals that carbon productivity was notably higher in the EU-15 countries than in other OECD countries, (the only exceptions being the EU member state Greece and the EFTA country Norway). While Slovenia had already reached the carbon productivity level of the USA and Canada, transition countries such as Poland and Estonia were still lagging behind in their carbon productivity in 2010-2015.

6. Concluding discussion

In this study we have estimated the average yearly cost of GHG abatement per capita for 28 OECD

countries during 1990-2015. The estimation was based on the observed changes in the GHG emissions and the marginal abatement cost estimates obtained by convex quantile regression, which is a novel data-driven approach that does not require restrictive assumptions about the functional form of the production function or the distributions of inefficiency and noise, but rather, estimates the shadow prices of GHG based on standard axioms of production at the observed level of performance.

Our empirical estimates of GHG abatement cost confirm that the EU countries bear a larger cost of GHG abatement than those OECD countries that did not keep their initial commitments to the Kyoto targets. According to our results, however, the GHG abatement is not nearly as expensive as the most pessimistic forecasts in the late 1990s projected. This is due to the fact that most estimates completely ignore inefficiency in production as well as input-side abatement alternatives.

Reliable empirical estimation of abatement cost is critically important for policy making. We believe that the perceived prohibitively high price of GHG abatement was the main reason why the USA never ratified the Kyoto Protocol and is currently taking steps to withdraw from the Paris Agreement. If academic research can convincingly demonstrate that the actual cost has been much lower than that portrayed in the most pessimistic forecasts in the late 1990s, then it would be easier to convince the future policy makers to pursue more ambitious GHG reductions that are considered necessary by the scientific community (IPPC, 2018). We hope that this study can be a first step in this direction, motivating further empirical research on this critically important topic.

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Appendix: Additional tables and figures related to the application

Table A1: Descriptive statistics of inputs, outputs and price variables

Variable	Unit	Mean	Median	Std. dev.	Min	Max	<i>n</i>
Output <i>y</i>	10 ⁹ €	762.09	199.48	1810.48	5.26	12041.41	728
<i>GHG</i>	10 ⁶ tons	469.98	81.08	1264.10	3.23	7349.07	728
Capital <i>K</i>	10 ⁹ €	2462.97	684.13	5688.29	0.96	36549.94	728
Labor <i>L</i>	10 ⁹ h	23.33	6.98	46.76	0.28	263.92	728
Wage <i>W</i>	€/h	13.66	12.83	9.01	0.03	47.49	728

Table A2: Productive performance of countries relative to quantile frontiers in selected years

	1990	2000	2010	2015	Legend:
Australia	(6,7)	(3,4)	(3,4)	(3,4)	1 = above 95th quantile
Austria	(8,9)	(8,9)	(8,9)	(8,9)	(1,2) = between 85th and 95th quantile
Belgium	(4,5)	(3,4)	(2,3)	(2,3)	(2,3) = between 75th and 85th quantile
Canada	1	1	1	1	(3,4) = between 65th and 75th quantile
Czech Republic	10	10	(9,10)	(9,10)	(4,5) = between 55th and 65th quantile
Denmark	(9,10)	(5,6)	(3,4)	(2,3)	(5,6) = between 45th and 55th quantile
Estonia	(5,6)	(6,7)	(8,9)	(8,9)	(6,7) = between 35th and 45th quantile
Finland	(8,9)	(4,5)	(4,5)	(4,5)	(7,8) = between 25th and 35th quantile
France	(8,9)	(6,7)	(3,4)	(2,3)	(8,9) = between 15th and 25th quantile
Germany	(6,7)	(5,6)	(4,5)	(3,4)	(9,10) = between 5th and 15th quantile
Greece	(2,3)	(3,4)	(4,5)	(9,10)	10 = below 5th quantile
Hungary	10	10	(9,10)	(9,10)	
Iceland	(9,10)	(6,7)	(8,9)	(5,6)	
Ireland	(5,6)	1	1	(1,2)	
Israel	(3,4)	1	1	1	
Italy	(2,3)	(2,3)	(5,6)	(5,6)	
Korea	(5,6)	(7,8)	(7,8)	(7,8)	
Latvia	10	10	10	(9,10)	
Luxembourg	1	1	1	1	
Netherlands	(7,8)	(3,4)	(3,4)	(2,3)	
New Zealand	(6,7)	(4,5)	(3,4)	(3,4)	
Norway	(2,3)	1	1	1	
Poland	(9,10)	(3,4)	1	1	
Slovak Republic	10	10	(9,10)	(9,10)	
Slovenia	10	(8,9)	(7,8)	(5,6)	
Sweden	(2,3)	(1,2)	(1,2)	1	
United Kingdom	(1,2)	1	1	1	
United States	(6,7)	(3,4)	(3,4)	(2,3)

Figure A1: Illustration of the output isoquants of quantiles $\tau = 0.05, 0.15, \dots, 0.95, 1$. The capital and labor inputs are held constant at their sample average.

Figure A2: Illustration of the input isoquants of quantiles $\tau = 0.05, 0.15, \dots, 0.95, 1$. The output and GHG are held constant at their sample average.

Figure A3: Development of marginal abatement costs of EU-15 counties during 1990-2015 (€²⁰¹⁰).

Figure A4: Development of marginal abatement costs of EFTA counties during 1990-2015 (€²⁰¹⁰).

Figure A5: Development of marginal abatement costs of EU transition economies during 1990-2015 (€²⁰¹⁰).

Figure A6: Development of marginal abatement costs of non-European OECD counties during 1990-2015 (€²⁰¹⁰).