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POLICY WATCH

Measuring climate policy stringency: a shadow price approach

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Abstract To assess the effect of environmental policy on production structures, trade structures, or foreign direct investment, a measure for the stringency of policy is necessary. Measures typically used in empirical studies share several disadvantages: they are not available on a sectoral basis to reflect concerns of industry competitiveness; they are not available for a wide range of countries to allow for international comparisons; or they are not broad enough to reflect the multidimensionality of environmental policy. This paper develops a thorough, internationally comparable, sector-specific measure of multidimensional climate policy stringency where a shadow price approach serves as a basis. The approach is applied to climate policy by determining sector-specific emission-relevant energy costs on the basis of the sectors' usage of emission-relevant energy carriers and the carriers' respective prices. The resulting shadow price estimates are heterogeneous and can be applied in future research to test for carbon leakage and pollution havens.

Keywords Environmental policy stringency · Climate policy stringency · Shadow price · Energy price · Pollution haven effect · Carbon leakage

JEL Classification H23 · H32 · H87

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1 Introduction

A long-lasting debate in environmental economics concerns the question whether a more stringent environmental policy causes changes in trade structures and relocations of industry. The fear is that industries reduce domestic production or relocate to countries with less stringent regulations. If such pollution haven effects[1] exist, they can at least in the short run have adverse consequences, e.g., lower income and employment. Despite the fact that the empirical evidence for significant pollution haven effects is ambiguous (Levinson and Taylor 2008), fears that a stricter policy might reduce the competitiveness of regulated industries have a significant impact on policy. In the third phase of the European Union emission trading system from 2013 onward, competitiveness considerations were used to justify the special and favorable treatment of certain industries (Dröge 2009). Similarly, while the costs for supporting renewable energies in Germany are passed on to consumers, energy-intensive industries have been granted generous exemptions to avoid rising energy costs and decreasing competitiveness (Diekmann et al. 2012).

The fear that regulation has adverse impacts is especially pronounced in the field of energy policy as a part of climate policy. If carbon-intensive production processes are shifted to countries with less strict mitigation policies, an additional negative consequence arises with carbon leakage and its impact on the effectiveness of unilateral climate policy regulation. While a broad body of the literature analyzes the pollution haven effects for pollution with strong local effects (Bao et al. 2011; Ederington et al. 2004; He 2006), only little empirical evidence exists on how climate policy affects a country's competitiveness and growth through the policy's impact on trade flows or relocation of carbon-intensive production. This lack of empirical research is at least partially the result of the unavailability of an internationally comparable sector-specific measure of climate policy stringency.

To evaluate pollution haven effects and carbon leakage empirically, it is necessary to find a measure for the stringency of policy.[2] The climate policy mix complicates the determination of a sector-specific climate policy stringency measure. Measures based on the direct assessment of single regulations in their mere nature cannot take interactions between several policies into account. Aggregate enforcement measures such as the number of implemented policies have a shortcoming in reflecting the characteristic of the policy as being, for instance, mandatory and restricting versus voluntary and supportive. This plurality of the implemented energy-related policies to reduce greenhouse gas emissions is reflected in Fig. 1 for a set of 28 countries, which are analyzed in more detail in this paper.[3] As can be seen, the USA is by far the country

[1] While Ederington et al. (2004) distinguish between a direct and an indirect effect, Copeland and Taylor (2004) similarly differentiate between a pollution haven effect and a pollution haven hypothesis.

[2] To thoroughly analyze issues such as carbon leakage, such a stringency measure constitutes the first step as it measures the impact of policy on specific sectors. But pollution haven and carbon leakage effects also depend on the intensity of competition in certain industries. Felbermayer et al. (2013) develop a measure for the intensity of competition based on trade costs, price elasticities, and (inter)national inter-sectoral linkages of value chains.

[3] For a detailed list of the included countries, please see Table 1.

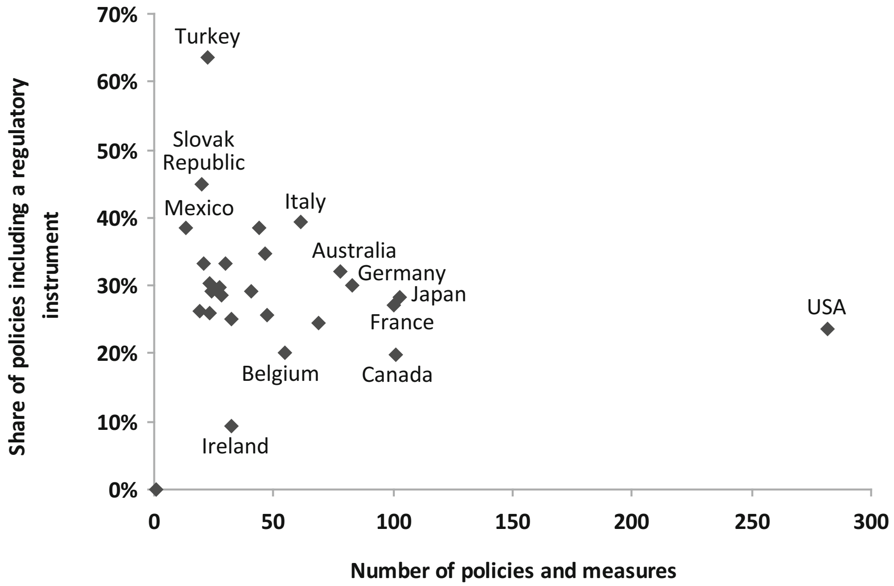

Fig. 1 Implemented energy-related policies and measures to reduce greenhouse gas emissions for a selected set of 28 countries in June 2013 (self-prepared using IEA (2013a))

with the largest number of implemented policies, but a comparatively low share of policies included a regulatory instrument and the USA is generally not known as the forerunner in climate protection.[4] Hence, in order to credibly analyze carbon leakage, an economist would favor a policy stringency measure reflecting actual private sector abatement costs, which vary across countries, across industries, and over time (Brunel and Levinson 2013).

Existing empirical literature merely uses measures, which cannot reflect this heterogeneity or face conceptual problems (Brunel and Levinson 2013). In addition, the indicators of environmental policy stringency mostly do not allow for appropriate international comparisons (van Soest et al. 2006). This may be one of the reasons why the majority of studies on pollution havens either are about the USA and other developed countries (Althammer and Mutz 2010; Keller and Levinson 2002) or are single-country studies (Bao et al. 2011; He 2006). However, in order to further the findings that in particular transition economies and the developing world may suffer detrimental increases in emissions resulting from trade (Managi et al. 2009), it is of utmost importance that a climate policy stringency measure can also be determined for non-highly developed countries. The same holds true for implemented regulations to abate global greenhouse gas emissions. The majority of stringency indicators measure environmental policy in general but not climate policy in specific.[5]

[4] In general, the estimated sector-specific climate policy stringencies in this paper do not change this perception.

[5] An overview of the environmental and climate policy stringency measures can be found in Sect. 2.1.

For these reasons, this paper develops a thorough, internationally comparable, sector-specific measure of multidimensional climate policy stringency. Thereby, van Soest et al.'s (2006) shadow price approach on environmental policy serves as a basis. They characterize their approach as a first attempt to quantify such a measure, because due to data availability their analysis had to be restricted to only two sectors in nine Western European countries for the time period 1978–1996. This paper extends the analysis of van Soest et al. (2006) in several aspects. First, a large dataset is used, covering 28 OECD countries including former transition economies and newly industrialized countries and 33 sectors from 1995 to 2009. Hence, with a special emphasis on greenhouse gas emissions, effects of the Kyoto Protocol and the transformation process after the fall of the Iron Curtain can be included in the analysis. Second, van Soest et al. (2006) do not look exclusively at emission-relevant energy carriers, but include all energy carriers, meaning also carbon-neutral ones, as polluting inputs. Therefore, their results cannot be interpreted as a measure of climate policy stringency, but rather as a measure of energy policy. A major innovation of this paper is the determination of sector-specific energy prices across a large set of countries covering seven carbon-related energy carriers. Third, from a technical point of view, their shadow prices are estimated for only three time periods and, thus, are strongly influenced by the development of the average market price. Extending the number of time periods allows for more variability in the shadow prices to account for country-specific changes in policy. The resulting shadow price estimates are heterogeneous and can be applied in future research to test for carbon leakage and pollution havens in a multicountry setting.

In the next section, the existing literature on empirical measures of environmental and climate policy stringency is reviewed. Then, in Sects. 2.2 and 3 the general idea of the shadow price approach and the applied methodology to the topic of climate policy are presented. After explaining the used data in Sect. 4, the results of the seemingly unrelated regressions and the estimated shadow prices are provided, discussed, and compared to other measures in Sect. 5. Section 6 concludes.

2 Literature

2.1 Environmental and climate policy stringency

There exist numerous approaches on the empirical measurement of environmental policy stringency as a whole and some on climate policy regulation in specific.[6] Brunel and Levinson (2016) structure the environmental policy approaches into five groups, namely private sector abatement costs, the direct assessment of individual regulations, composite indices, measures based on pollution or energy use, and measures based on public sector efforts. While the five categories are not entirely mutually exclusive, they include the most important streams of literature. A similar overview is provided by Sauter (2014) for cross-country measures that are available for at least ten countries.

[6] An extensive overview of environmental policy stringency approaches can be found in Brunel and Levinson (20013b).

Millimet and Roy (2016) review the research on instrumental variables used for environmental stringency. As to date only little research has been carried out exclusively on climate policy stringency, the categories of Brunel and Levinson (2016) are adopted in the following and the selected articles on climate policy regulation are structured accordingly.

A common approach to measuring environmental policy stringency is to determine private sector pollution abatement costs, which reflect how much more costly firms' production in a given jurisdiction is relative to others as a result of complying with regulations. The data are often obtained with the help of surveys by directly asking industry managers about their pollution abatement expenditures. For instance, Levinson (1996) and List and Co (2000) use the annual United States Pollution Abatement Costs and Expenditures (PACE) data, the earliest and most prominent example for this type of survey data. Pasurka (2008) provides a summary of estimates outside of the USA including European countries as well as the questionnaire of the Organisation for Economic Co-operation and Development (OECD). In general, the idea of the surveys of determining a cardinal cost number directly coincides with the data needed to measure stringency. However, the questionnaires face both the conceptual problem that respondents may not be able to correctly separate corporate expenditures with an environmental intent from the ones with a profit motive and the weakness that all types of abatement costs, even those which cannot be directly attributed to environmental regulation, are included (Brunel and Levinson 2016). Pasurka (2008) adds that it is difficult to make international comparisons based on the different surveys. As only expenditures of existing companies are represented, the questionnaires may also over- or understate the costs for new firms (Morgenstern et al. 2001). An alternative approach to measuring private sector abatement costs without using the expenditure questionnaires is the shadow price approach. The idea of the shadow price approach, which this paper follows, will be introduced from Sect. 2.2 onward.

In contrast to measuring the costs implied in all environmental regulation, the second stream of literature narrowly focuses on specific regulations. On the one hand, this is done by utilizing the existence of natural experiments such as the National Ambient Air Quality Standards (NAAQS), which the Clean Air Act in the USA required to be set for six air pollutants. Henderson (1996) uses the NAAQS to analyze the effects of local regulation and finds that greater regulatory efforts in non-attainment counties improve the air quality and result in a relocation of polluting industries to avoid regulatory scrutiny. The launch of the emission trading scheme in the European Union is studied in Kettner et al. (2008) and Yu (2011). While the former measure the differences in stringency in the 24 member states and find that small installations are treated differently from big ones, the latter does not find significant impacts on Swedish energy firms' profits. On the other hand, the ratification and strictness of individual regulations is used as a measure of overall environmental or climate policy stringency. Nakada (2006) examines the relationship between income distribution and the timing of the ratification of the Kyoto Protocol. In order to test for pollution havens, Cole et al. (2006) use the allowed lead content in gasoline. These measures are sensitive to several obstacles, in particular to the multidimensionality of regulations as well as simultaneity (Brunel and Levinson 2016). The narrow focus of individual regulations and natural experiments limits the generalizability of the results. Given that individual regulations are also dissimilar across countries makes it difficult to create a consistent regulation-based measure of stringency across countries.

The third type of measure rests on compressing the multidimensional regulatory environment down to one holistic index number. An extensive overview of composite indices evaluating country performance from an economic, political, social, and environmental viewpoint is given by Bandura (2008). In order to construct an environmental policy stringency index, often surveys serve as a basis. In an early attempt, Walter and Ugelow (1979) build an index, which ranks countries on a scale from one, referring to strict, to seven, referring to tolerant, based on the responses of the questionnaire collected by the United Nations Conference on Trade and Development (UNCTAD). Dasgupta et al. (2001) develop a more extensive index for 31 countries using 500 different observations per country from the reports prepared for the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992. An environmental stringency index that includes a climate change sub-index is calculated in Cagatay and Mihci (2006) based on the pressure–state–response model of the OECD. Künkel et al. (2006) specifically develop a climate policy index to measure actual policy stringency at the national and the sectoral level for 1992, 1997, and 2005 using predominantly readily available data sources such as the OECD and the International Energy Agency (IEA). Even though these composite indices help to incorporate multiple regulations in one cardinal value, the assessment of the scales can be difficult.[7] Furthermore, the indices are often only available for one cross section and cannot be disaggregated by pollutant (Sauter 2014). While the weighting of the included factors is merely ad hoc limiting the robustness of the indices, the survey indices are based on perceptions and, thus, may be potentially biased.

Measures based on pollution or energy use make use of the relationship between these indicators and environmental regulation. While Xing and Kolstad (2002) as well as Costantini and Crespi (2008) interpret high levels of sulfur dioxide or carbon dioxide emissions on the country level as a sign of low stringency, McConnell and Schwab (1990) assume that high levels of air pollution on the county level force regulators to take actions and, hence, coincide with a high stringency. This inherent simultaneity constitutes a main disadvantage of indices based on pollution or energy use (Brunel and Levinson 2013). Alternatively, percentage reductions in carbon dioxide emissions are used in Javorcik and Wei (2003) to measure environmental policy stringency. Cole and Elliot (2003) apply energy intensity data as a stringency index. However, these proxies only expose information on quantities consumed rather than expenditures taken, which at the same time require information on prices.

Lastly, in order to indirectly reflect the regulatory stringency, researchers sometimes use public sector efforts related to the environment, which has the advantage of incorporating an enforcement dimension (Brunel and Levinson 2016). Whereas Gray (1997) and Magnani (2000), respectively, use public expenditures for environmental and natural resources in general and environmental protection in specific, Levinson (1996) includes the number of employees at state environmental agencies relative to the number of manufacturing plants. Analyzing a panel of 29 Chinese provinces

[7] List and Co (2000) solve this problem by ranking states based on their weighted public and private sector pollution abatement expenditures in dollars.

between 1992 and 2004, Bao et al. (2011) use a combination of indicators including the government pollution abatement expenses and the number of employees in environmental protection-related agencies. The mere shortcoming of these measures lies in their ambiguity as a proxy of stringency, because some types of public expenditures such as tax incentives relieve the private sector from costs. Moreover, the relative differences in the size of the administrative body across countries complicate an international application.

2.2 The shadow price approach

Like the PACE survey, the shadow price approach aims at determining private sector abatement expenditures as a measure for environmental policy stringency. There exist a number of articles, which calculate pollution abatement costs with the help of shadow prices by including pollutants either as inputs or as outputs in the technology. Both Coggins and Swinton (1996) and Färe et al. (2005) determine the shadow price of sulfur dioxide emissions in the electricity generation sector. While the former analyze 14 coal power plants in Wisconsin from 1990 to 1992, the latter looks at 209 fossil fuel power plants in the USA in the years 1993 and 1997. The phosphorus content of manure is considered as the polluting output in Huhtala and Marklund (2006), who measure its shadow price in the animal agricultural sector in Finland during the period from 1994 to 2002. Using a sample of 30 pulp and paper mills in Wisconsin and Michigan, Pittman (1981) represents an early approach to include pollutants as inputs in order to estimate marginal abatement costs. van Soest et al. (2006) measure the shadow price of energy use for the heavy metals and the food processing industry for nine Western European countries from 1978 to 1996. By considering energy as the polluting input, which is certainly used in all sectors, their method has the potential to be applied as a measure of environmental policy stringency across a larger set of sectors and geographical coverage as well as over time.

The shadow price approach is based on microeconomic theory and the choices made by companies reflecting their profit maximization behavior. van Soest et al. (2006, p. 1155) "define the shadow price of an input as the potential reduction in expenditures on other variable inputs that can be achieved by using an additional unit of the input under consideration (while maintaining the level of output)." Hence, in the case of no regulation, the price for a polluting input is low and a profit-maximizing firm will use relatively more of the polluting input and less of other variable inputs to produce the same quantity of output. If the regulation is more stringent, e.g., because of a new tax or quota, the price of the polluting input will increase and the firm will use relatively less of the polluting input (Brunel and Levinson 2016). In other words, regulation drives a wedge λ_E between a company's shadow price Z_E for an additional unit of the polluting input E and the input's undistorted market price p_E (Morrison Paul and MacDonald 2003; van Soest et al. 2006):[8]

[8] The interpretation of Z_E and p_E of van Soest et al. (2006) slightly differs from the one of Morrison Paul and MacDonald (2003), who differentiate between the observed price p and the effective/shadow price Z.

$$Z_E = p_E + \lambda_E \tag{1}$$

Given that markets are sufficiently integrated internationally, the undistorted market price can be represented by the world price of the polluting input (van Soest et al. 2006). The wedge is then a measure of stringency reflecting either a stricter or a weaker environmental policy regulation than the world average. A positive wedge results in the shadow price being larger than the undistorted market price, indicating that the company's or sector's usage of the polluting input is restricted. A negative wedge points at a low stringency and a subsidized usage of the polluting input.

The underlying shadow prices and wedges can be determined by assuming that firms are profit maximizing, which coincides with a cost minimization in the case of competition. This is done by estimating a firm's or sector's cost function with the help of the information revealed in firm's behavior, i.e., data on the level of output, the quantities of all inputs including the polluting input, and the prices of all inputs but the ones of the polluting input.

The shadow price approach overcomes several shortcomings of the other mentioned approaches. A major shortcoming concerns the multidimensionality of climate policies (Brunel and Levinson 2016). The general aim of climate policy is limiting global warming by reducing greenhouse gas emissions. This can be achieved by reducing the use of fossil fuels in the energy mix, increasing the share of renewable energies, fostering energy efficiency, creating carbon sinks, and other mitigation policies. The instruments used encompass voluntary approaches like industry self-commitments, command-and-control approaches like fuel-efficiency standards, and market-based policies like taxes, tradable permits, and subsidies. As shown in Fig. 1, governments use several of these instruments at the same time. Therefore, measuring the stringency of policy and comparing it across countries becomes a demanding task. The shadow price approach offers a specific solution: Whenever policy affects the shadow price of carbon-related energies, the choice of a firm concerning carbon-related energy inputs changes. A tax on carbon-related inputs directly drives a wedge between the shadow price and the undistorted market price. Tradable permits create a similar difference yielding an implicit tax rate. Furthermore, the indicator can deal with integrated technologies, because substitution possibilities between factors of production are incorporated. Given that all companies in a specific sector are considered, the shadow price approach controls for the industrial composition as well as capital vintage and, thus, the effect of regulation on investments (Brunel and Levinson 2016). Finally, general equilibrium effects like an increase in demand for non-polluting inputs and their prices affect the shadow price.

One of the drawbacks is that policies that do not affect the shadow price are not covered by the stringency measure. If a company voluntarily reduces the use of polluting inputs or if end-of-pipe technologies are commanded, the shadow price does not change. It should be noted that the shadow prices are a reflection of any policies or market impacts on the costs of the polluting input including government policies other than purely environmental ones and market failures. Yet, this may be seen as an advantage when it comes to assessing the location choice of certain industries from a more comprehensive view (van Soest et al. 2006). Furthermore, the estimates do not merely reflect the stringency faced by new entrants and appropriately treating endogenous technological progress is cumbersome. Lastly, the results are partly impacted by the selected functional form of the cost or production function as well as the choice of inputs and outputs requiring a careful inspection of the regression estimates (Brunel and Levinson 2016).

By estimating the abatement costs for a certain pollutant, shadow prices summarize the hidden implications of all direct and indirect regulations in one cardinal cost measure. Therefore, the shadow prices and certainly the resulting wedges allow for comparing the actual policy stringency faced by firms in different sectors, across countries, and over time even if the policy instruments implemented differ. The covered literature in the beginning of this section also shows that shadow prices can be determined for different kinds of pollutants. All things considered, the shadow price approach is the preferred method for determining the private sector abatement costs of climate policy regulation that are of relevance for the analysis of pollution havens and carbon leakage.[9]

3 Methodology

To determine each sector's climate policy stringency, the shadow price approach is applied to emission-relevant energy costs. For this reason, the respective shadow prices along with a comparatively larger number of wedges are calculated. This is done by estimating a generalized Leontief (GL) cost function and the shadow price equation (1) with the help of a system of seemingly unrelated regressions and by applying Shephard's lemma. The estimated coefficients are then in turn used for the quantification of the sector-specific shadow prices and the wedges.

Diewert and Wales (1987) introduce a GL cost function, which adds technical change and scale economies to the traditional function. An extension is suggested by Morrison (1988) and Morrison and Schwartz (1996) that facilitates the inclusion of additional inputs, such as variable inputs where the shadow price can deviate from the market price, and permits a closed-form derivation of the long-run equilibrium levels of the inputs. By this, the advantages of the GL function are preserved, i.e., linear homogeneity in prices and variable input demand functions that are homogenous of degree zero and linear in the parameters facilitating the estimation. At the same time, the drawbacks of other functional forms like translog functions or normalized quadratic cost functions are not shared (Morrison 1988). This paper follows the estimation approach of Morrison Paul and MacDonald (2003) and van Soest et al. (2006) who directly include the shadow price of the input under consideration in the cost function.[10] By this, the polluting input is treated as a variable input with a shadow price allowed to deviate from the (undistorted) market price due to regulation. The used variable cost function C in its general form with an arbitrary number of inputs and exogenous

[9] For further discussion of advantages and disadvantages of the shadow price approach, see van Soest et al. (2006, pp. 1158-60).

[10] Looking at the US food processing sector, Morrison Paul and MacDonald (2003) found differences between the observed and the shadow price for capital and agricultural goods, but not for labor, energy, and two materials inputs. The alternative approach used by Morrison (1988) and Morrison and Schwartz (1996) nests the quantities of the input under consideration instead of their prices in the cost function.

variables to account for scale effects and the state of technology reads as follows:[11]

$$
\begin{aligned}
C = {} & y\left[\sum_L\sum_M \alpha_{LL} p_L^{0.5} p_M^{0.5} + \sum_L\sum_E \alpha_{LE} p_L^{0.5} Z_E^{0.5} + \sum_E\sum_F \alpha_{EE} Z_E^{0.5} Z_F^{0.5}\right] \\
& + y\left[\sum_L\sum_A \delta_{LA} p_L s_A^{0.5} + \sum_L p_L \sum_A\sum_B \gamma_{AB} s_A^{0.5} s_B^{0.5}\right] \\
& + y\left[\sum_E\sum_A \delta_{EA} Z_E s_A^{0.5} + \sum_E Z_E \sum_A\sum_B \gamma_{AB} s_A^{0.5} s_B^{0.5}\right] \\
& + y^{0.5}\left[\sum_L\sum_K \delta_{LK} p_L x_K^{0.5} + \sum_L p_L \sum_A\sum_K \gamma_{AK} s_A^{0.5} x_K^{0.5}\right] \\
& + y^{0.5}\left[\sum_E\sum_K \delta_{EK} Z_E x_K^{0.5} + \sum_E Z_m \sum_A\sum_K \gamma_{AK} s_A^{0.5} x_K^{0.5}\right] \\
& + \sum_L p_L \sum_K\sum_Q \gamma_{KK} x_K^{0.5} x_Q^{0.5} + \sum_E Z_E \sum_K\sum_Q \gamma_{KK} x_K^{0.5} x_Q^{0.5}
\end{aligned}
\tag{2}
$$

Thereby, p_L is the price of the variable input L and the subscripts L and M refer to variable inputs. Z_E is the shadow price of the polluting input E, and the subscripts E and F denote variable inputs where the shadow price may be different from the market price. The stock of the quasi-fixed input K is given by x_K, and the subscripts K and Q represent quasi-fixed inputs. S, which is enumerated by the subscripts A and B, stands for exogenous arguments in the cost function such as the output level y and time t as a proxy for the state of technology.[12] Finally, the respective coefficients are given by α, γ, and δ.

In order to estimate the coefficients in the cost function, factor demand functions for both types of variable inputs can be derived based on Shephard's lemma. In addition, input–output ratios are employed to adjust for different sector sizes:[13]

$$
x_L y^{-1} = y^{-1} \partial C\left(p, Z, x, y, \bullet\right) / \partial p_L \tag{3}
$$

[11] The literature on production functions provides several extensions of GL functions. For instance, Nakamura (1990) presents a non-homothetic extension of the GL cost function, which allows a broader modelling of scale effects and technological change. Data restrictions prevent us from modeling these aspects in more detail. A similar argument applies to Behrmann et al.'s (1992) extension of a CET–CES Leontief variable profit function, which allows expanded input and output substitution possibilities at the cost of introducing one additional parameter to be estimated.

[12] For now, additional sub-subscripts are for clarity reasons left out. In the final estimating model each coefficient is also classified with regard to its country, sector, and time specification.

[13] Other authors use the input–output specification to correct for potential heteroscedasticity, which this paper adjusts for by estimating robust standard errors (Morrison 1988; Morrison and Schwartz 1996; van Soest et al. 2006).

and

$$x_E y^{-1} = y^{-1} \partial C\left(p, Z, x, y, \bullet\right) / \partial Z_E \tag{4}$$

As consistent sector-specific data are only available for the relatively short time period of 15 years, which coincides with a limited number of degrees of freedom, further assumptions need to be implemented. Given that empirical researchers have found it difficult to isolate the independent impacts of technology, the factor inputs, and the returns to scale, long-run constant returns to scale are assumed to adapt the generality of the cost function (Morrison 1988). Hence, the long-run output elasticities for both variable and quasi-fixed inputs are set equal to one. Moreover, time trends are only utilized in the estimation of the shadow price equation outlined in Eq. (8). Both assumptions translate into setting $\delta_{LA} = \delta_{EA} = \gamma_{AB} = \gamma_{AK} = 0$.

For the purpose of estimating the cost function, three input factors are used. Labor L is considered as a fully variable input; emission-relevant energy E is the variable input where due to causes such as climate regulation a wedge can be driven between the shadow price and the market price; and capital K is assumed to be a quasi-fixed input. As a result, the final specification of the variable cost function can be written as:

$$\begin{aligned} C = {} & y\left[\alpha_{LL} p_L^{0.5} + \alpha_{LE} p_L^{0.5} Z_E^{0.5} + \alpha_{EE} Z_E^{0.5}\right] + y^{0.5}\left[\delta_{LK} p_L x_K^{0.5} + \delta_{EK} Z_E x_K^{0.5}\right] \\ & + \gamma_{KK} p_L x_K^{0.5} + \gamma_{KK} Z_E x_K^{0.5} \end{aligned} \tag{5}$$

According to Shepherd's lemma, taking the partial derivatives of Eq. (5) with respect to the price of labor p_L and the shadow price of energy Z_E gives the conditional factor demand function. Furthermore, to save degrees of freedom and following Morrison (1988) the interaction effects are assumed to be specific for every sector i, but common across all countries c and time t, whereas the direct effects represented by the coefficients α_{EE} and α_{LL} are set to be common across time, but both sector-specific and country-specific:

$$x_L y^{-1} = 0.5\alpha_{LL,i,c} p_L^{-0.5} + 0.5\alpha_{LE,i} p_L^{-0.5} Z_E^{0.5} + \delta_{LK,i} y^{-0.5} x_K^{0.5} + \gamma_{KK,i} y^{-1} x_K^{0.5} \tag{6}$$

and

$$x_E y^{-1} = 0.5\alpha_{EE,i,c} Z_E^{-0.5} + 0.5\alpha_{LE,i} p_L^{0.5} Z_E^{-0.5} + \delta_{EK,i} y^{-0.5} x_K^{0.5} + \gamma_{KK,i} y^{-1} x_K^{0.5} \tag{7}$$

Besides the system of input–output equations, information about the shadow value of the variable input energy is included for estimation purposes. Therefore, the shadow price equation (1) is specified in more detail:

$$Z_E = \beta_{\bar{E},i} p_E + \lambda_{E,i,c,t} D_i D_c D_t \tag{8}$$

Thereby, the (undistorted) market price p_E is given by an average sector-specific (world) market price and its effect is allowed to differ across sectors (van Soest et al. 2006). $\beta_{\bar{E}}$ represents the coefficient of the (undistorted) market price. In order to reconcile the limited number of degrees of freedom with an in-depth analysis of the climate policy stringency, sector- and country-specific wedges for five equally long time periods are estimated.[14] In other words, the wedges are estimated as a markup or markdown by including an interaction effect of the dummy variables D of each sector, each country, and the time periods 1995–1997, 1998–2000, 2001–2003, 2004–2006, and 2007–2009.

The final estimating model consists of three equations: namely the two input–output functions (6) and (7) and the detailed shadow price equation (8). The estimation is carried out by using seemingly unrelated regressions, a method that has been first specified by Zellner (1962) and allows for the estimation of common coefficients across a system of equations. In order to reflect possible fixed effects and given that each coefficient is at least sector-specific, the individual sectors are estimated independently, reducing the complexity for the statistical program at the same time. Robust standard errors are determined to correct for potential heteroscedasticity. As a last step, the estimated coefficients are used to calculate the shadow prices and the wedges as the sector-specific, internationally comparable measure of climate policy stringency.

4 Data

4.1 Data sources and description

For the implementation of the described cost function estimation, price and quantity information on the production output, the capital and labor employed, and the energy consumption are required. The data are derived from the World Input–Output Database (WIOD), the Penn World Tables (PWT), the IEA, and the OECD. Except for the energy price data from the IEA (2013b) and the capital investment information from the PWT (2011, 2012), which is needed for the capital stock estimation,[15] only existing variables from the WIOD (2012a, b) are used. Exchange rates and country-specific price indices are taken from the OECD (2012a, b). Currency conversion has been applied to all monetary variables using the exchange rates as well as country- and sector-specific deflators. As the estimated shadow prices are in later research intended to be utilized as a thorough measure for climate policy in order to test for pollution haven or carbon leakage effects, all monetary units are calculated in 2005 prices but not in purchasing power parity. In other words, the goal is to test for misdirecting incentives for investors or plant owners rather than to represent the point of view of a social planner.[16]

[14] The results are robust to alternative time periods, which may be of the same or different lengths.

[15] Given that WIOD does not offer sector-specific capital stock information for the whole time period under consideration, the capital stock data are constructed using the methodology explained in Appendix 1.

[16] Shadow prices have also been estimated using PPP units. This resulted in a tendency of higher shadow prices for poorer countries, which can be interpreted such that poorer economies spend a relatively higher

Table 1 Country overview (in total, 28 countries)

Asia and Oceania (4 countries)
Australia, Japan, Korea, Turkey
America (3 countries)
Canada, Mexico, USA
Eastern Europe (6 countries)
Czech Republic, Estonia, Hungary, Poland, Slovak Republic, Slovenia
European Union 1995 (15 countries)
Austria, Belgium, Denmark, Finland, France, Germany, Great Britain, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden

The final variables are:

- gross output y measured in billions of 2005 US dollars
- the capital stock x_K in billions of 2005 US dollars
- employment x_L in millions of man-years worked
- the average wage p_L in thousands of 2005 US dollars
- the emission-relevant energy use x_E in millions of tons of oil equivalent
- the energy price Z_E and the sector-specific average market energy price p_E in thousands of 2005 US dollars per ton of oil equivalent

With the exception of the average market energy price, all variables are time- and sector-specific at the country level. The constructed database covers information on 28 countries disaggregated into 33 sectors[17] over a time period of 15 years from 1995 to 2009. This corresponds to more than 13,500 observations compared to roughly 300 observations on nine countries and two sectors in van Soest et al. (2006) and, therefore, allows for a more detailed application of the approach. Table 1 provides an overview of all included nations.

The 28 countries and 33 agricultural, industrial, and service sectors are in accordance with the structure of the main data source WIOD, which organizes the sectors based on the division-level ISIC Rev. 3.1[18] classifiers. Due to insufficient data on either energy prices or capital stocks, several countries from the original database and the sectors air transport (ISIC 62) and private households with employed personnel (ISIC 95) are excluded. Nevertheless, the final dataset covers the whole range of primary, secondary, and tertiary sectors as well as a comparatively large number of countries including former transition economies from Eastern Europe and the newly industrialized countries Mexico and Turkey. In addition, the effects of the Kyoto Protocol and of the integration of the former Eastern Block countries can be analyzed.

share of income on emission-relevant energy use or, in other words, on costs resulting from climate policy regulation.

[17] Table 6 in Appendix 2 lists all included 33 sectors.

[18] ISIC refers to the International Standard Industrial Classification of All Economic Activities.

4.2 Energy price computation

One important reason why van Soest et al.'s (2006) approach—despite its advantages over other measures—has not yet been applied to a larger set of countries and industries is the lack of consistent data on energy prices on the sectoral level. Thus, a major innovation of this paper represents the determination and subsequent application of sector-specific energy prices across the comparatively large set of countries. The energy prices in this paper are in general calculated as a weighted average based on the prices of seven energy carriers used and the associated carriers' sector-specific volumes.

The country-specific data of the IEA on industry and household energy prices of seven energy carriers, namely electricity, coal, natural gas, diesel, gasoline, heavy fuel oil, and light fuel oil, are used as the foundation. In the first step, missing values of these energy prices are determined using the respective PAASCHE price indices. As the IEA also provides a country-specific total energy PAASCHE price index, the average energy price of the remaining energy sources Z_E^{REST} can be calculated with the help of this index, the derived prices of the seven energy carriers, and the associated gross energy uses $x_{E^{Total}}$ given in WIOD.[19] In doing so, it is necessary to assume that the weighted average energy price Z_E^{KNOWN} of the seven energy carriers j in some (base) year 0 is equal to the price of the remaining sources in the same year and, consequently, also to the total average industry or household energy price $\bar{Z}_E$:

$$Z_{E_{0,c}}^{KNOWN} = \left(\sum_j Z_{E_{0,j,c}} x_{E_{0,j,c}^{Total}} \right) \Big/ \sum_j x_{E_{0,j,c}^{Total}} = Z_{E_{0,c}}^{REST} = \bar{Z}_{E_{0,c}} \tag{9}$$

For every country c, the year with the highest explained share of the seven energy carriers in the total gross energy use is chosen as the (base) year.[20] The final energy prices, which are specific for every sector i and only include emission-relevant energy use, are then given by a weighted average of the energy carriers' prices, and their sector-specific emission-relevant energy uses x_E:

$$\begin{aligned} Z_{E_{t,i,c}} &= \left(\sum_j Z_{E_{t,j,c}} x_{E_{t,i,j,c}} + Z_{E_{t,c}}^{REST} x_{E_{t,i,c}}^{REST} \right) \Big/ \left(\sum_j x_{E_{t,i,j,c}} + x_{E_{t,i,c}}^{REST} \right) \\ &= \left(\sum_j Z_{E_{t,j,c}} x_{E_{t,i,j,c}} + Z_{E_{t,c}}^{REST} x_{E_{t,i,c}}^{REST} \right) \Big/ x_{E_{t,i,c}} \end{aligned} \tag{10}$$

[19] The gross energy use includes the use of both energy carriers that are relevant for emissions and the ones that do not emit.

[20] If all observations are included—also the ones that are not in the base years—the seven energy sources on average make up 86 % of the total sectors' energy use, which is relevant for emissions and, hence, for climate policy issues. As for some years data are not available for all seven energy carriers, the explained share in the base years only is even higher and, therefore, considered a reasonable estimate for the respective year's average energy price. In the remaining years, the total average energy price is determined by the total energy PASCHE price index. The final shadow prices have been tested for robustness and do not reveal significant differences compared to estimates using alternative base years with similar explained shares of energy use.

For this computation, the industry prices of the energy carriers have been assigned to all industry sectors and the household prices to the service and agricultural sectors.[21] Two exceptions constitute heavy fuel oil and gasoline, where only industry prices for the former and household prices for the latter are available and are, therefore, assigned to all sectors. The rationale is that for the set of analyzed countries automobile gasoline is assumed to be primarily sold at publicly available gas stations, which serve customers from all sectors. Similarly, in the rare instances that a non-industry customer purchases heavy fuel oil, it is believed that they are likely to participate in the same market as industrial clients.

In addition, the (undistorted) market energy price needs to be determined. Following van Soest et al. (2006), who calculate an average market price across their nine analyzed European nations, a sector-specific average market price across all 28 countries c, which includes emission-relevant energy use only, is employed. The average market energy price p_E is calculated as a weighted average of the individual sector- and country-specific energy prices in a particular year t and the respective emission-relevant energy uses, which are used as weights:

$$p_{E_{t,i}} = \left(\sum_c Z_{E_{t,i,c}} x_{E_{t,i,c}} \right) \Big/ \sum_c x_{E_{t,i,c}} \tag{11}$$

5 Results and discussion

In the following, the estimated results from the cost function approach are presented for two exemplary sectors. Then, the characteristics of the measure are discussed in general, and subsequently, the results are compared to other measures.

5.1 Analysis of two exemplary sectors

Given the large size of the dataset including 33 sectors in 28 countries, first the results of two exemplary sectors are presented and discussed in more detail to analyze the structure of the estimated shadow prices and respective wedges. One potential application of the climate policy stringency measure is to determine whether pollution haven effects and carbon leakage exist. For this reason, based on the amended carbon leakage list of the European Commission (2012), the chemicals and chemical products sector as well as the inland transport sector are selected. While the former sector is potentially prone to carbon leakage, the latter one in theory should not be.

Table 2 provides a selected part of the regression results of the chemicals and the inland transport sector. In order to account for the limited space, a complete overview of the estimated regression results can be found in Table 8 in appendix 4 (Online resource 1). The regression estimates of the remaining sectors are happily provided upon request.

[21] Table 7 in Appendix 3 summarizes the allocation of industry and household prices of the energy sources to the sectors.

Table 2 Selected regression results

	Chemicals and chemical products	Inland transport
	Coefficient[a] (SE)	Coefficient[a] (SE)
Common coefficients		
α_{LE}	−0.001*** (0.000)	0.000 (0.000)
δ_{LK}	0.000 (0.000)	−0.001*** (0.000)
δ_{EK}	0.015*** (0.003)	0.006*** (0.001)
γ_{KK}	0.001*** (0.000)	0.005*** (0.001)
$\beta_{\bar{E}}$	1.341*** (0.076)	1.287*** (0.056)
Netherlands		
α_{LL}	0.017*** (0.001)	0.058*** (0.003)
α_{EE}	0.047*** (0.002)	0.021*** (0.002)
$\lambda_{E,95\text{-}97}$	−0.131*** (0.009)	0.827*** (0.105)
$\lambda_{E,98\text{-}00}$	−0.128*** (0.008)	0.490*** (0.034)
$\lambda_{E,01\text{-}03}$	−0.130*** (0.009)	0.377*** (0.019)
$\lambda_{E,04\text{-}06}$	−0.114*** (0.011)	0.467*** (0.025)
$\lambda_{E,07\text{-}09}$	−0.019 (0.019)	0.496*** (0.056)

[a] Significance codes: * $p < .10$; ** $p < .05$; *** $p < .01$

In the upper part of Table 2, the coefficient estimates that are assumed to be sector-specific and equal across all countries are presented. In the case of the chemicals sector, the substitution coefficient α_{LE} is significant and negative, supporting the idea that labor and energy can be substitutes. The interaction coefficients δ_{LK} and δ_{EK} are not restricted by theory. The significant coefficient estimates for $\beta_{\bar{E}}$ denote the effect of a change in the market price on the shadow price and are positive as expected. Yet, the coefficients of the capital stock γ_{KK} reveal an unexpected sign as they are significantly positive. In theory, one expects that variable costs will decline if the capital stock increases. This unexpected sign is estimated in numerous other studies on cost structures. Filippini (1996) discusses possible interpretations such as an excessive amount of capital stock or multicollinearity between the output and the capital stock.

Concerning the country- and sector-specific coefficients, an inspection of the estimated direct effects α_{EE} and α_{LL} of the variable inputs energy and labor reveals no significant negative coefficient for all countries, which supports the validity of the selected functional form. In other words, the estimated signs are as expected and a price increase in one of the variable inputs, ceteris paribus, generally results in a rise in variable costs. The global concavity condition concerning the variable input prices of energy and labor and the global convexity condition regarding the quasi-fixed input capital have been ensured by computing the second-order partial derivatives of the variable cost function (5).

The estimated wedge coefficients λ_E can serve as a first indicator for the stringency of climate regulation. For instance, in the case of the Netherlands the coefficient is negative and highly significant for the chemicals sector until the year 2006 and positive and highly significant for the inland transport sector for every time period. This hints at an initial subsidization and subsequent reduction of the preferential treatment of the chemicals sector and a restrictive climate policy for the inland transport sector.

Based on the estimated coefficients, the sector-specific shadow prices can be quantified. Table 9 in appendix 5 (Online resource 1) provides a list of all sector-specific shadow prices.[22] A respective ranking of the 28 countries according to their average shadow price is shown for the two exemplary sectors in Table 3.[23] The shadow prices are compared to the end-1970s to the mid-1990s environmental policy stringency estimates of van Soest et al. (2006) in a similar range but larger, which affirms the credibility of the results and may be explained by generally higher regulatory efforts since then and by the later base year in this paper. The average shadow prices also support the first impression of the wedge coefficients. In particular, the ranking for the inland transport sector confirms popular opinions about climate policy stringency with Germany along with the majority of the other Western European countries having the strictest regulations and the Northern American countries the weakest. This reflects the different emission-relevant energy costs borne by the transport sector in each country, i.e., predominantly cost differences in the fuels caused by regulation.

The transport sector is especially interesting, because this sector is heavily taxed and data availability allows comparing this paper's results with the ones of other studies. According to OECD (2013), transport accounts for 23 % of total energy use and 27 % of the carbon dioxide emissions generated in an average OECD country. Due to high tax rates, the transport sector generates on average 85 % of total excise taxes from energy products in OECD countries. Thereby, the effective tax rate on transport fuels (in EUR per ton of carbon dioxide) ranges from EUR 8.1 in Mexico to EUR 262.87 in Great Britain with an average of EUR 160.53 (OECD 2013). The four countries with the lowest effective tax rate in the OECD report are identical to those with the lowest average shadow price in Table 3. If one compares the country ranking based on the effective tax rate in the transport sector as reported in the OECD study with the respective ranking in Table 3, a Spearman correlation coefficient amounting to 0.75 is estimated.[24] This supports the hypothesis that shadow prices reflect regulatory distortions.

Interestingly, the regional distribution for the chemicals sector in Table 3 is much more diverse. While the Netherlands is among the Western European forerunners regarding climate policy stringency in the inland transport sector, it is the only Western European nation placed in the fourth quartile in the chemicals industry. Moreover, four out of the five countries with the lowest climate policy stringency in the chemicals sector are either a former transition economy or a newly industrialized country proving potential incentives for carbon leakage.

Table 3 also displays the minimum and maximum levels of the shadow prices between 1995 and 2009, which show considerable differences and are a first indication for large variation inherited in the measure over time. This large variation in the measure is confirmed by the temporal development of the estimated wedges for the

[22] In addition, both the estimated wedge coefficients and the shadow prices are provided in an Excel dataset (Online resource 2).

[23] The rankings look the same based on the wedge coefficients.

[24] In this comparison, one needs to bear in mind that the OECD reports effective tax rates in 2012, whereas Table 3 shows average shadow prices for the time period 1995 to 2009. Given the fact that many countries increased the taxes over the last two decades at unequal rates, the estimated correlation is relatively high.

Table 3 Country ranking for the two exemplary sectors based on the average shadow price

Chemicals and chemical products						Inland transport					
		Avg	(SD)	Min	Max			Avg	(SD)	Min	Max
1	Italy	0.894	(0.276)	0.615	1.363	1	Germany	1.657	(0.309)	1.319	2.293
2	Slovenia	0.886	(0.195)	0.610	1.139	2	Denmark	1.434	(0.317)	1.137	2.115
3	Japan	0.802	(0.077)	0.685	0.911	3	Sweden	1.431	(0.206)	1.150	1.880
4	Luxembourg	0.783	(0.294)	0.480	1.280	4	Netherlands	1.403	(0.266)	1.047	1.931
5	Portugal	0.715	(0.128)	0.540	0.927	5	Great Britain	1.402	(0.254)	1.039	1.852
6	Ireland	0.713	(0.126)	0.582	0.967	6	Austria	1.390	(0.265)	1.061	1.953
7	Germany	0.635	(0.131)	0.488	0.877	7	Italy	1.306	(0.341)	0.983	1.990
8	Denmark	0.627	(0.200)	0.424	0.990	8	Belgium	1.239	(0.299)	0.929	1.839
9	Belgium	0.610	(0.130)	0.457	0.845	9	France	1.193	(0.312)	0.906	1.836
10	Finland	0.594	(0.125)	0.447	0.826	10	Ireland	1.188	(0.285)	0.902	1.772
11	Hungary	0.588	(0.202)	0.366	0.933	11	Turkey	1.182	(0.486)	0.744	2.105
12	Sweden	0.583	(0.130)	0.444	0.817	12	Slovenia	1.179	(0.375)	0.664	1.766
13	Austria	0.577	(0.166)	0.395	0.881	13	Finland	1.144	(0.257)	0.887	1.715
14	Greece	0.540	(0.116)	0.417	0.768	14	Portugal	1.119	(0.387)	0.794	1.910
15	Korea	0.530	(0.079)	0.419	0.686	15	Luxembourg	1.111	(0.213)	0.868	1.606
16	Great Britain	0.509	(0.125)	0.370	0.735	16	Hungary	1.108	(0.350)	0.737	1.741
17	France	0.493	(0.110)	0.362	0.679	17	Japan	1.093	(0.141)	0.937	1.472
18	Spain	0.485	(0.106)	0.367	0.689	18	Poland	1.018	(0.408)	0.609	1.799

Table 3 continued

Chemicals and chemical products						Inland transport					
		Avg	(SD)	Min	Max			Avg	(SD)	Min	Max
19	Slovak Republic	0.462	(0.219)	0.245	0.863	19	Czech Republic	1.008	(0.378)	0.656	1.773
20	Mexico	0.447	(0.137)	0.270	0.657	20	Greece	0.990	(0.359)	0.670	1.723
21	Canada	0.423	(0.087)	0.316	0.565	21	Spain	0.967	(0.346)	0.627	1.639
22	USA	0.419	(0.042)	0.364	0.493	22	Estonia	0.912	(0.338)	0.588	1.571
23	Netherlands	0.411	(0.140)	0.274	0.680	23	Slovak Republic	0.892	(0.373)	0.499	1.683
24	Estonia	0.405	(0.139)	0.260	0.636	24	Korea	0.882	(0.353)	0.546	1.549
25	Turkey	0.396	(0.163)	0.258	0.717	25	Australia	0.871	(0.198)	0.661	1.325
26	Poland	0.341	(0.095)	0.216	0.510	26	USA	0.589	(0.176)	0.409	1.004
27	Czech Republic	0.334	(0.111)	0.227	0.558	27	Mexico	0.518	(0.113)	0.354	0.777
28	Australia	0.330	(0.068)	0.227	0.454	28	Canada	0.504	(0.114)	0.388	0.810

In thousands of 2005 US dollars per ton of oil equivalent

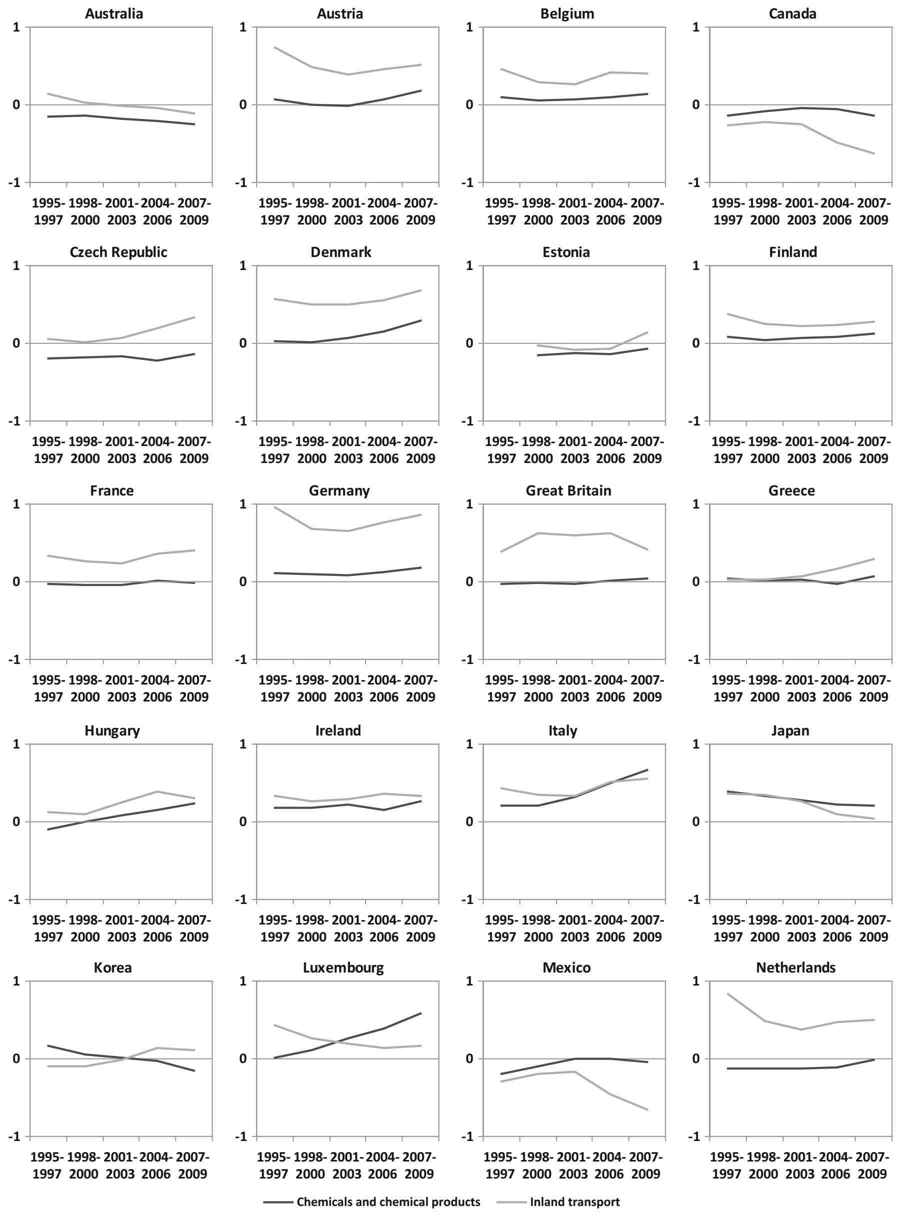

Fig. 2 Country-wise overview of wedges (in thousands of 2005 US dollars per ton of oil equivalent)

two sectors presented in Fig. 2. As explained in Sect. 2.2, a positive wedge is estimated when the shadow price is higher than the (undistorted) market price, i.e., the country's industry is stricter regulated. A negative wedge implies an implicit subsidy to the respective sector on its use of fossil fuels or electricity. Figure 2 with the wedges displayed on the y-axes shows that a heterogeneous development seems to exist not only internationally, but also within the same country and over time.

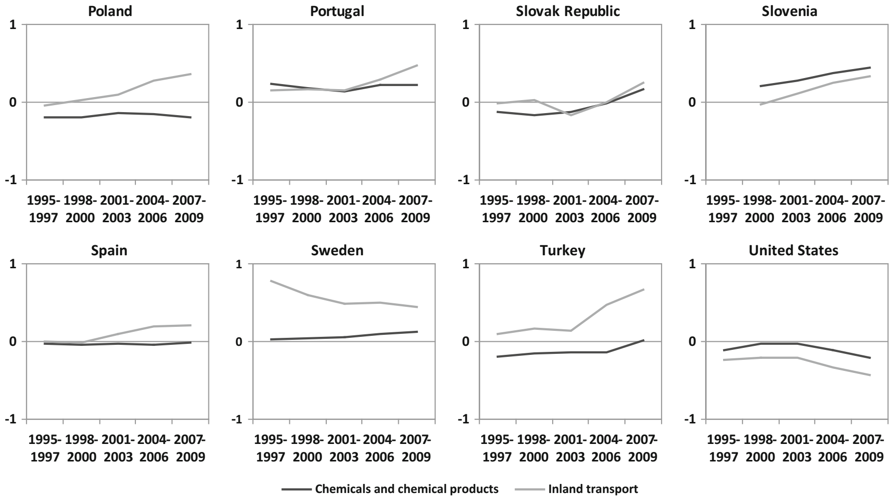

Fig. 2 continued

5.2 General characteristics of the shadow prices and the wedges

Three deductions can be derived from the analysis of the two exemplary sectors, which also hold true for the estimates of the remaining sectors. Firstly and most obviously, countries lay different weights on climate policy regulation. Whereas, e.g., the USA has a relatively low stringency across all 33 sectors with 97 % of the sectors being in either the third or fourth quartile of the rankings, Germany as a representative of the Western European countries has a comparatively high stringency with 94 % of the sectors being in first and second quartile. This impression is validated by Table 4, which shows the country ranking of the shadow prices on an aggregated level across all sectors as well as across manufacturing and service sectors only. Taking all sectors into account, the USA has on average the 25th highest shadow price as opposed to Germany that places sixth among the 28 analyzed countries.

At the same time, Table 4 reveals regional differences in stringency. The majority of Western European countries can be found in the first and second quartile not only on average across all sectors, but also when analyzing the aggregated manufacturing and service sectors separately. The opposite holds true for the Northern American along with the Eastern European countries that on average place in the third and fourth quartile. Moreover, on the sectoral level some regions show similar developments in stringency as can be seen in Tables 10 and 11 in appendix 6 (Online resource 1) for the two exemplary sectors. The wedges of the inland transport sector of the Northern American countries are very highly positively correlated with each other, and at the same time negative correlation coefficients are displayed between the Northern American countries and the Eastern European as well as the majority of Western European countries. This indicates regionally integrated markets in the inland transport sector and that North America is heading down a different road with regard to climate policy stringency than Europe during the analyzed time period. Similarly, in the chemicals

Table 4 Country ranking for aggregated sectors based on the weighted average shadow price

	All sectors					Manufacturing sectors			Service sectors		
	Rank	Avg	(SD)	Min	Max	Rank	Avg	(SD)	Rank	Avg	(SD)
Denmark	1	1.715	(0.881)	0.193	3.313	7	0.708	(0.195)	1	2.110	(0.681)
Italy	2	1.291	(0.455)	0.387	2.500	1	0.978	(0.428)	5	1.479	(0.378)
Sweden	3	1.261	(0.502)	0.363	2.052	11	0.640	(0.127)	2	1.569	(0.302)
Japan	4	1.260	(0.446)	0.141	2.110	3	0.857	(0.213)	4	1.492	(0.365)
Austria	5	1.205	(0.529)	0.225	2.387	12	0.595	(0.217)	3	1.501	(0.390)
Germany	6	1.136	(0.460)	0.147	2.364	8	0.707	(0.172)	6	1.393	(0.419)
Portugal	7	1.131	(0.409)	0.296	2.162	6	0.721	(0.234)	7	1.337	(0.367)
Luxembourg	8	1.107	(0.310)	0.292	1.606	5	0.762	(0.256)	13	1.168	(0.273)
Netherlands	9	1.063	(0.477)	0.175	2.133	23	0.502	(0.191)	8	1.337	(0.345)
Ireland	10	1.057	(0.366)	0.370	1.943	4	0.811	(0.221)	10	1.205	(0.369)
Great Britain	11	1.038	(0.399)	0.194	1.870	13	0.591	(0.169)	9	1.212	(0.327)
Slovenia	12	0.999	(0.274)	0.429	1.766	2	0.902	(0.229)	18	1.053	(0.299)
Spain	13	0.994	(0.383)	0.249	1.956	15	0.582	(0.161)	11	1.188	(0.353)
Belgium	14	0.968	(0.352)	0.171	1.839	10	0.647	(0.203)	14	1.130	(0.333)
Greece	15	0.944	(0.328)	0.277	1.723	16	0.579	(0.193)	17	1.060	(0.299)
France	16	0.892	(0.325)	0.255	1.836	21	0.520	(0.151)	19	1.041	(0.263)
Finland	17	0.886	(0.308)	0.294	1.715	14	0.591	(0.140)	15	1.084	(0.231)
Turkey	18	0.884	(0.386)	0.035	2.105	18	0.557	(0.230)	16	1.065	(0.316)
Korea	19	0.866	(0.372)	0.140	1.549	20	0.541	(0.167)	12	1.180	(0.266)

Table 4 continued

	All sectors					Manufacturing sectors			Service sectors		
	Rank	Avg	(SD)	Min	Max	Rank	Avg	(SD)	Rank	Avg	(SD)
Australia	20	0.805	(0.316)	0.227	1.502	27	0.453	(0.185)	20	0.956	(0.224)
Estonia	21	0.757	(0.285)	0.237	1.571	22	0.515	(0.146)	22	0.883	(0.250)
Slovak Republic	22	0.744	(0.423)	0.172	2.519	19	0.553	(0.253)	23	0.876	(0.476)
Hungary	23	0.714	(0.298)	0.275	1.741	9	0.649	(0.227)	26	0.762	(0.339)
Poland	24	0.709	(0.343)	0.088	1.799	28	0.413	(0.169)	21	0.915	(0.307)
USA	25	0.683	(0.207)	0.232	1.203	24	0.467	(0.133)	25	0.764	(0.182)
Czech Republic	26	0.619	(0.344)	0.152	1.773	26	0.455	(0.257)	24	0.766	(0.351)
Mexico	27	0.614	(0.171)	0.201	1.004	17	0.567	(0.163)	27	0.672	(0.146)
Canada	28	0.580	(0.159)	0.254	0.993	25	0.462	(0.125)	28	0.649	(0.154)

In thousands of 2005 US dollars per ton of oil equivalent

Table 5 Country-wise correlation coefficients between the wedges of the chemicals and the inland transport sector

Australia	0.997	Great Britain	−0.681	Poland	−0.182
Austria	0.723	Greece	0.509	Portugal	0.855
Belgium	0.794	Hungary	0.783	Slovak Republic	0.803
Canada	0.639	Ireland	−0.005	Slovenia	0.998
Czech Republic	0.319	Italy	0.956	Spain	0.363
Denmark	0.975	Japan	0.993	Sweden	−0.816
Estonia	0.867	Korea	−0.778	Turkey	0.800
Finland	0.558	Luxembourg	−0.766	USA	0.994
France	0.677	Mexico	−0.197		
Germany	0.990	Netherlands	0.515		

sector the wedges of the Western European countries are, apart from minor exceptions for France, all positively correlated between each other and negatively correlated with the wedges of Canada and the USA.

Secondly, within countries sectors are in part treated differently. In Table 5, both highly positive and highly negative correlation coefficients are found between the wedges of the chemicals and the inland transport sector inside the same country. A similar picture appears for intra-country correlations among other sectors. This may be the result of different policy regulations faced by the sectors, e.g., in order to protect certain sectors from international competition or to restrain carbon leakage, but can also indicate that the impact of regulation varies across sectors. Interestingly, on the aggregated level, as displayed in Table 4, it can be observed that on average for each country the abatement costs per emission-relevant energy unit are higher for service sectors than for manufacturing sectors. In other words, service sectors seem to face stricter relative climate policy regulation. Yet, as energy-intense industries use higher amounts of emission-relevant energy, their total abatement costs are higher. In this respect, the shadow price measure seems to closely reflect reality given that manufacturing sectors in general or energy-intense industries in specific are occasionally relieved from the costs of (climate) policy regulation and that large industrial consumers are likely to have a higher bargaining power.[25]

Thirdly, the sector-specific climate policy stringency is heterogeneous over time. In the most extreme cases, some countries change within the 15-year time period from relatively subsidizing a certain sector to a restrictive policy and vice versa. For instance, for the chemicals sector Korea starts with a positive and highly significant wedge for the period 1995–1997 and ends with a negative and highly significant wedge for the period 2007–2009. For the inland transport sector, the picture is the opposite. While this variability over time is likely to be in part attributed to changes in the regulatory environment, it seems unlikely that the heterogeneity of the shadow price measure

[25] There exist quite a number of examples for the differentiated treatment of sectors including the implementation of the European Union Emission Trading System and the distribution of the costs of the German Renewable Energy Act.

can be matched with an equal variability of the individual regulations. Hence, the estimated measure allows analyzing the actual stringency faced by firms and private investors in the market. This is seen to be of utmost importance to facilitate testing for misdirecting incentives of climate policy regulation.

5.3 Comparison to alternative measures

As the last step of the discussion, the estimates of the shadow price indicator are compared to other measures of environmental and climate policy stringency. For this reason, additional indicators are derived by extending the data with supplementary information from the environmental accounts of the main data source WIOD. The 18 sector-specific indicators that all fall into the category of measures based on pollution or energy use as reviewed in Sect. 2.1 can be classified into three groups: namely gross energy use per output, greenhouse gas emissions per output, and reductions in greenhouse gas emissions or in gross energy use per output. Gross energy use per output is commonly used as a measure of sector-specific energy efficiency. Besides the price of energy, energy use is one of the determinants of the energy costs and a production input. By arguing that strict regulation may limit the consumption of polluting energy carriers and result in increased energy efficiency, research has used energy intensity as a measure of environmental policy stringency before. Greenhouse gas emissions as a polluting output are a direct result of using emission-relevant energy carriers such as fossil fuels. As indicated before, both high and low levels of emissions have been used as a measure of stringency. For the following eight gases, emission intensities are calculated: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), mono-nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), and ammonia (NH_3). In addition, reductions in emission intensities and in energy intensities are determined. Earlier researchers interpret relatively large reductions as a reaction to stricter regulatory constraints. In general, data are available for the whole time period from 1995 to 2009 for all 28 countries and 33 sectors included in the dataset.[26] For the reductions in intensities values can be calculated from 1996 to 2009.

Tables 12 and 13 in appendix 6 (Online resource 1) show the correlation coefficients between the different measures for the chemicals and the inland transport sector. On the one hand, some moderate and high correlations can be observed between indicators of the same group and between energy intensity and the emission intensities. For instance, for both sectors the shadow prices are highly correlated to the wedges and correlation coefficients above 0.50 can be found between the carbon dioxide emission intensity and both the energy intensity and the intensity of mono-nitrogen oxides. Not surprisingly, this reconfirms the significant relationship between the wedges and the shadow prices and indicates that the use of energy entails polluting a mix of emissions. On the other hand, there exist no high correlations between measures of different groups, i.e., the shadow prices and the wedges are not highly correlated to any other measure and the gross intensities are not highly correlated to the reduction in intensities. Thus, the high

[26] Nevertheless, the dataset contains some missing data points.

variability of the shadow price indicator, which is derived using both energy price and quantity information, cannot be matched by measures focusing on only one of the two dimensions or their effects.

The findings are supported by van Soest et al. (2006), who compare a methodologically similar sector-specific shadow price measure of environmental policy stringency to four other countrywide indicators and find no high correlations between the indicators. Namely, the share of environmental tax revenues of the total revenues from taxes and social contributions, the ratio of public environmental R&D expenditures to the GDP, the per capita membership in environmental organizations, and the lead content in gasoline are compared to the shadow prices of energy. van Soest et al. (2006) conclude that countrywide measures are not good indicators in explaining variations in international competitiveness between sectors as differences in regulatory stringency exist both between countries and between sectors within one country.

6 Conclusion

Given the need for a theoretically consistent, internationally comparable, sector-specific measure of multidimensional climate policy stringency, this paper for the first time applies the shadow price approach of environmental policy stringency to the topic of climate policy. Annual shadow prices and the respective wedges, which indicate the regulatory stringency, are estimated based on sector-specific emission-relevant energy costs. For this reason, sector-specific energy prices are determined with the help of the prices of seven common emission-relevant energy carriers and their corresponding sector-specific usage. The high degree of detail incorporated in the data and the focus on shorter 3-year time periods for the wedges allow for estimating a heterogeneous measure with increased variability over time. The climate policy stringency is computed for 33 primary, secondary, and tertiary sectors for a comparatively large set of 28 OECD countries between 1995 and 2009. Not only highly developed countries, but also former transition economies from Eastern Europe and the newly industrialized countries Mexico and Turkey are included in the analysis. These are potential locations for outsourcing activities in the 1990s and the beginning of the twenty-first century for Western European and Northern American companies and, therefore, of interest for applying the measure in future research.

While the primary aim of the analysis is to develop an internationally comparable measure of policy stringency in the field of climate policy that can be used in future studies to determine the effect of regulation on a variety of regressands, the study itself also has policy implications. Given that environmental and climate policy are multidimensional using different instruments with special provisions for different sectors, the joint evaluation of the policy stance at the sectoral level may be rather cumbersome. By providing a cardinal measure of policy stringency, the shadow price estimates enable such an evaluation. The results may even give rise to rethink the special treatment of certain sectors.

Despite the large coverage of the dataset, the study leaves room for improvement predominantly owing to the unavailability of data. First, the number of non-highly developed economies can be further increased by also including developing and non-

OECD countries, allowing for an even greater applicability of the measure. Prospects for this are good, because the United Nations Statistical Division has launched a project to extend the main data source WIOD in both geographical and time coverage (Sauter 2014). Thus, the estimation of the shadow prices and wedges can then be continued for the years after 2009, which is considered to be important to examine the future development of climate policy stringency while fighting climate change.[27] As a result of the limited number of 28 included countries, the average market price may not necessarily reflect the world market average in the case of insufficiently internationally integrated input markets. Hence, the wedges may merely represent a comparative measure of climate policy stringency across the included set of countries.[28] However, this does not limit the applicability as a relative measure of stringency, because the international ranking of and the differences between the shadow prices as well as the wedges are not altered. A second disadvantage is that the energy prices are like in van Soest et al. (2006) measured in average terms. Certainly marginal prices of energy would be preferred, but in order to determine them, additional information, e.g., about substitution possibilities, is required. Moreover, the estimated climate policy stringency measure does not solve the above-mentioned general weaknesses of shadow price approaches, namely the focus on cost data for existing firms and the dependence on the selected functional form of the cost function.[29]

All in all, it is believed that the estimated shadow prices and wedges are a strong cardinal measure of climate policy stringency. Consequently, an extension of the time frame and the geographical coverage is, subject to the availability of the data, regarded as one of the tasks of future research. Given that the measure reflects sector-specific private compliance costs and is available for primary, secondary, and tertiary sectors, it may help to clarify how climate policy abatement efforts influence economic activity in a multicountry setting. Potential applications are not limited to the discussion about the existence of carbon leakage and pollution havens. One may also test for impacts of climate policy stringency on greenhouse gas emissions, labor markets, and innovation or for implications of historic events like the fall of the iron curtain and the Kyoto Protocol. This paper provides estimates of a thorough relative measure of climate policy stringency to analyze these different policy concerns.

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[27] In other words, the measure is likely not to become another one that cannot be further extended due to the unavailability of data. Examples for this are the indices of Dasgupta et al. (2001) and Eliste and Fredriksson (2002).

[28] For instance, a negative estimated wedge may only indicate that the country is subsidizing the usage of the polluting input relative to the rest of the included countries.

[29] With regard to the cost function explained in Sect. 3, this paper follows the approach of van Soest et al. (2006), who take all cost information as exogenously given and, hence, cannot explain changes in explanatory variables of the cost function.

stakeholders from politics, industry, and society. Concerning the refinement of the paper, we would like to thank two anonymous referees for their valuable comments. Moreover, we benefited from discussions with participants of the 5th WCERE 2014, the 71st Annual Congress of the IIPF 2015, and the Annual Conference of the German Economic Association 2015.

Appendix 1: Capital stock computation

The WIOD only offers sector-specific capital stock information until 2007. For this reason, the capital stock data are constructed by applying the perpetual inventory method to the PWT data and disaggregating the country-level estimates with the help of the information in WIOD on the shares of each sector in the total national capital stock.

The capital stock x_K is constructed using the perpetual inventory method explained in Caselli (2005), who computes the capital stock in time t as the sum of the real aggregate capital investments I_t in the respective year and the depreciated capital stock of the previous year:[30]

$$x_{K_t} = I_t + (1 - \delta)\, x_{K_{t-1}} \tag{12}$$

Here, δ refers to the depreciation rate. The initial capital stock in the year 1995 is determined following common practice by dividing the investments in 1995 by the sum of the depreciation rate and geometric mean growth rate g of the investments for the whole time period from 1995 to 2009:

$$x_{K_{1995}} = I_{1995}\, (g + \delta)^{-1} \tag{13}$$

As the PWT capital investments data are available in the country level only, a disaggregation scheme, which is derived from the WIOD sector-specific real fixed capital stock data, is used to disaggregate the capital stock estimates. The WIOD data are not used in the first place, because the WIOD offers no capital stock information for the years 2008 as well as 2009 and updating the WIOD data using prior growth rates seems to be problematic owing to expected negative consequences of the financial dept crisis that started in 2008. Therefore, the missing sector shares for 2008 and 2009 are replaced by the information given for the last available year in WIOD, namely 2007.

Appendix 2: Sector overview

See Table 6.

[30] The constructed capital stock measure has also been compared to the one reported in the Extended Penn World Tables 4.0. for all countries in WIOD and shows a very high correlation coefficient of 0.995.

Table 6 Included sectors and the respective division-level ISIC Rev. 3.1

ISIC Rev. 3.1	Sector
A–B (01–05)	Agriculture, hunting, forestry, and fishing
C (10–14)	Mining and quarrying
15–16	Food, beverages, and tobacco
17–18	Textiles and textile products
19	Leather, leather and footwear
20	Wood and products of wood and cork
21–22	Pulp, paper, printing, and publishing
23	Coke, refined petroleum, and nuclear fuel
24	Chemicals and chemical products
25	Rubber and plastics
26	Other non-metallic minerals
27–28	Basic metals and fabricated metal
29	Machinery, nec
30–33	Electrical and optical equipment
34–35	Transport equipment
36–37	Manufacturing, nec; recycling
E (40–41)	Electricity, gas, and water supply
F (45)	Construction
50	Sale, maintenance, and repair of motor vehicles and motorcycles; retail sale of fuel
51	Wholesale trade and commission trade, except for motor vehicles and motorcycles
52	Retail trade, except for motor vehicles and motorcycles; repair of household goods
H (55)	Hotels and restaurants
60	Inland transport
61	Water transport
63	Other supporting and auxiliary transport activities; activities of travel agencies
64	Post and telecommunications
J (65–67)	Financial intermediation
70	Real estate activities
71–74	Renting of M&Eq and other business activities
L (75)	Public admin and defense; compulsory social security
M (80)	Education
N (85)	Health and social work
O (90–93)	Other community, social, and personal services

Appendix 3: Distribution of industry and household prices

See Table 7.

Table 7 Distribution of industry and household prices of the seven energy carriers to the primary, secondary, and tertiary sector

	Electricity	Coal	Natural gas	Diesel	Gasoline	Heavy fuel oil	Light fuel oil
Agricultural sector	Household prices	Household prices	Household prices	Household prices	Household prices	Industry prices	Household prices
Industry sector	Industry prices	Industry prices	Industry prices	Industry prices	Household prices	Industry prices	Industry prices
Service sector	Household prices	Household prices	Household prices	Household prices	Household prices	Industry prices	Household prices

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