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Tradable Permits in Cost–Benefit Analysis

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Abstract

There is no consensus with respect to handling of tradable permits in cost–benefit analysis. The leading (organizational/governmental) manuals in North America, Europe, Asia, and Australia handle permits in different ways or ignore them. This paper offers a brief discussion of the properties of cap-and-trade systems, and contrast these to the properties of emission charges. The paper then turns to cost–benefit rules for projects using fossil fuels in a cap-and-trade system. The focus is on small projects but the paper also briefly addresses the case where a project significantly affect prices. As a service to the reader the small project rules are contrasted to the much more familiar and standardized ways of handling emission charges in cost–benefit analysis. Finally, the consequences of market power in cap-and-trade markets are briefly addressed.

Keywords: Cost–benefit analysis; greenhouse gases; tradable permits; emission charges; market power.

JEL-codes: H21; H23; H41; H43; I 30; L13.

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1. Introduction

According to the International Carbon Action Partnership (2015) there are 17 emissions trading systems in force across four continents, covering 35 countries, 12 states or provinces, and seven cities. The largest one is the European Union's EU Emissions Trading System (EU ETS) launched in 2005. It covers the European Economic Area (EEA), i.e., the 28 EU Member States plus Iceland, Liechtenstein, and Norway. In 2013 the EU ETS covered more than 12,000 power stations and industrial plants, as well as 1,300 airlines (since 2012). However, there are cap-and-trade systems also for other emissions. An example is provided by the US Acid Rain Program to reduce emissions of sulfur dioxide and nitrogen oxides. There are also cap-and-trade systems in other fields, for example, in fishery and for taxicabs.

The main purpose of this paper is to discuss how to design a cost–benefit analysis (CBA) of a project within a cap-and-trade-system, with special reference to the EU ETS. One reason for undertaking this exercise is that some of the leading cost–benefit manuals provide conflicting recommendations or are silent with respect to the treatment of permits. Both the Canadian manual and the manual of the US Environmental Protection Agency (EPA) view the cost of permits as a pure transfer between firms, i.e., there is no cost for society as a whole. (Treasury Board of Canada Secretariat (2007, p. 10); US EPA (2010, p. 9-16).) The 2014 guide by the European Commission's Directorate-General for Regional and Urban Policy argues that if a dynamic perspective is adopted, a project under evaluation should be credited for any future reduction in the number of permits valued at a shadow price reflecting the damage caused by emissions. (European Commission (2014, p. 225, footnote 266, p. 63, Table 2.10).) To the best of my knowledge, the European Investment Bank is currently (October 2015) assessing how to handle permits, but see European Investment Bank (2013) for latest available approaches. The UK Green Book, see UK Government (2011), was updated in 2014 to value emissions within the EU ETS using the permit price (i.e., not the global marginal damage cost). As far as I can see, the update does not explicitly address the question how a project within the EU ETS affects emissions. However, the 2009 background report quite clearly states that there are binding targets, i.e., no net impact on emissions within the EU ETS. Refer to UK Government (2014, pp. 8-9) and UK Government (2009, p. 24). The Asian Development Bank's guide from 2013, and the Australian Government's handbook from 2007 do not address the issue at all. (Asian Development Bank (2013); Australia Government (2006).) Checks of leading textbooks in environmental and public economics, searches on Google Scholar, and contacts with some leading academic cost–benefit analysts failed to provide any further guidance. This provides further justification for developing this paper.

The basic model used in this paper is static, although intertemporal generalizations are briefly considered in Appendix A. Allowing banking and borrowing of permits in a simple perfect foresight dynamic model, the optimal permit price increases at the discount rate, replicating Hotelling's (1931) rule for a nonrenewable resource; refer to Rubin (1996) and Kling and Rubin (1997). The reader interested in the price dynamics when the basic perfect market assumptions are relaxed is referred to Hasegava and Salant (2015), who review the literature on bankable emission permits which has developed over the last two decades. Tol (2013) reviews optimal targets for international climate policy in the short and long run, while Tol (2013) undertakes a cost–benefit analysis of the EU20/20/2020 package (the European Union aims to limit its 2020 greenhouse gas emissions to 80% of its 1990 emissions and to meet 20% of its energy needs by renewables.) In any case, because the aim of this paper is to derive cost–benefit rules for projects requiring permits, any discussion of the dynamics of permit prices or optimal targets is set aside, and markets are assumed to be perfect with the exception of emission of greenhouse gases. However, in Appendix C, the implications for cost–benefit analysis arising from market power are addressed.

The design of a permit system has significant distributional impact; see, for example, the recent assessment of the efficiency of the EU ETS by Laing et al. (2013). Allocating permits to firms free of charge (grandfathering) will result in a distribution that is different from the one resulting when permits are auctioned. The impression is that the Union is moving from grandfathering towards auctions. In this paper, it is typically assumed that an auction mechanism is applied and that the revenue stays with the national government. Setting aside distributional issues, the auction-assumption has no impact on the results. I will also introduce a unit tax on emissions of greenhouse gases in a region identical to the EEA, except that it lacks a cap-and-trade system. This is made as a service to the reader although taxes are covered by virtually every textbook on environmental and public economics. The revenues from a tax or a permit system opens up the possibility to cut other, harmful taxes. However, the aim of this paper is not to evaluate such shifts but to discuss the handling of permits, and contrast it to the handling of an emission charge, in cost–benefit analysis. Therefore, any revenue is returned to individuals in a lump-sum fashion.

The paper is structured as follows. Section 2 is devoted to a fossil fuel that either is covered by a cap-and-trade system or is subject to an emission tax. The impact on emissions of these policy instruments is discussed. The possibility of controlling emissions is introduced and the optimal level of emissions is considered. After this more general discussions, Section 3 applies cost–benefit analysis to a project using the fossil fuel as an input, given that there is a cap-and-trade system. How to handle reductions in the number of permits over time is also discussed. A brief discussion of how to evaluate a project that is so large that it significantly affects the permit price is added. Section 4 offers a discussion of how to handle an emission charge in cost—benefit analysis. Section 5 provides a few brief concluding remarks. Three appendices are added. Appendix A introduces the formal model underlying the discussion in this paper, and derives cost–benefit rules for marginal projects, both under a cap-and-trade system and under an emission charge. Appendix B details how to asses a project that has a significant impact on the permit price. Finally, Appendix C is devoted to a brief discussion of how to handle market power in permit markets in cost–benefit analysis.

2. Emission charges vs. emission permits on inputs

The focus is on inputs. Steel is produced using coal as one input. It is this input that causes emissions of greenhouse gases, not the steel itself. A car trip is "produced" using a car, roads, time, and gasoline as inputs. A meal can be seen as produced using fish, electricity or gas, time, and other inputs. In these and many other cases one can view emissions as a hidden input because it is directly related to an input (fossil fuel), but one may as well term it a second output along with the main output. These examples provide motivation for the focus on inputs.

Let us begin by comparing an *emission charge* and a *quota*. An emission charge is a fee levied on each unit of pollutant emitted into the air or water. Under a tradable permit system, all sources are required to have permits to emit. Each permit specifies how much the firm is allowed to emit. The permits are freely transferable, and there is (at each point in time) a fixed number of permits. In its simplest (Cobb–Douglas) form a demand function is $e = em = (p^x)^3/(p^e + p)^2$, where e is demand for the fossil fuel, em is the volume emitted, for simplicity assuming that the emission factor is unity, p^x is the output price, p^e is the unit price of the fossil fuel (here held constant), and p is the permit price (and all other prices are suppressed). Unless it causes confusion, the symbol e is used to denote both the quantity emitted and the quantity of the fossil fuel demanded/supplied. The curve looks identical if permits are replaced by an emission charge per unit emitted: $e = (p^x)^3/(p^e + t)^2$, where t denotes the rescaled emission charge. The higher the permit price or tax, the lower is demand for emissions, i.e., the less will the firm emit. If the cost of emitting becomes sufficiently high, one expects that emissions will become zero, but the detailed outcome depends on the properties of the production function. The location of the demand curve may shift over the business cycle, for example, due to shifts in the output price p^x.

Thus far the possibility of abatement has been ignored. If this option is available, the firm would abate until the marginal cost of abatement is equal to *p* (or *t*), and then emit. Thus abatement causes a counterclockwise rotation of the demand curve for emissions around the level where *p* (*t*) is equal to zero. Then net emissions to the air would be $em = (p^x)^3/(p^e + p)^2 - e^c$, where e^c denotes the optimal level of abatement for each permit price; replace *p* by *t* to obtain the case with an emission charge.

Under an emission charge, emissions are *endogenous* and will vary across the business cycle. In contrast, under a quota system, total emissions are controlled, i.e., are *exogenous*. If the authority has issued e^q permits e^q tons will be emitted, regardless of the level of economic activity. In this case the permit price, not the quantity of emissions, is endogenous and will vary over the business cycle. Hence there is a fundamental difference between emission charges and permits. In Fig. 1 the global marginal damage cost curve reflects the estimated cost of the marginal unit of emissions through its impact on the *stock* of emissions. Global emissions of greenhouse gases remain in the atmosphere for certain periods of time and are often assumed to only slowly degrade. Therefore, one must calculate the present value damage cost that each emitted unit causes. The longevity of CO_2 in the atmosphere is probably the least well understood part of the global warming issue, and there are estimates ranging from a few years to essentially forever. However, a present value, even if the discount rate is as low as 1.4%, as is the case in Stern's (2007) report on the costs of climate change, is not very sensitive to costs beyond year 200: increasing the time horizon from 200 years to 300 years increases the present value of a constant stream of money by less than 5%.

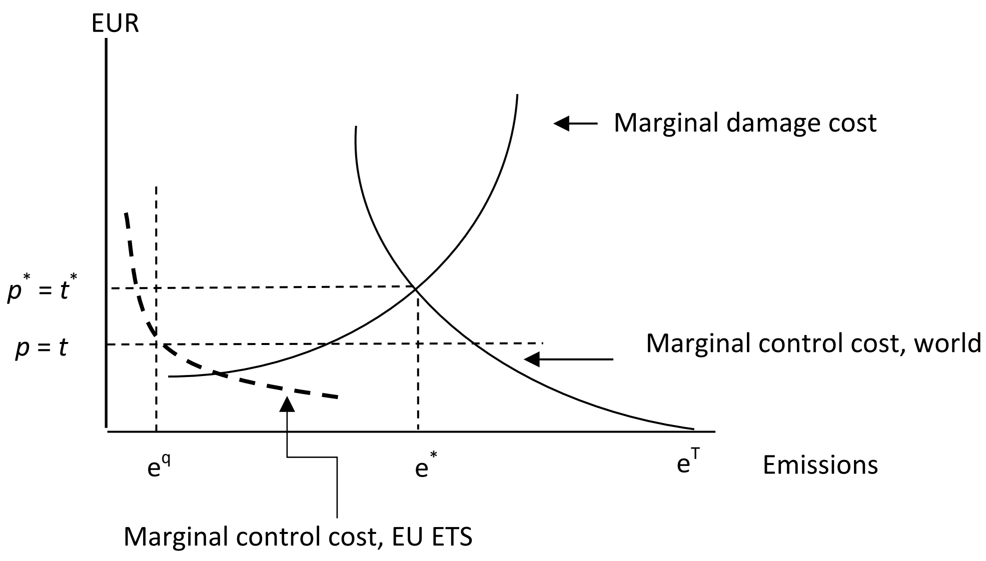

Fig. 1. Illustration of the optimal degree of emissions reduction.

There are also technologies for controlling the *flow* of emissions. For example, retro-fitting existing fossil fuel power plants and introducing new fossil fuel technologies can improve conversion efficiency or enable the capture and sequestration of CO_2 emissions. In Fig. 1 the worldwide marginal control cost increases in the volume of emissions controlled. One could view the marginal control cost curve as the global sum of demand curves of the type discussed above, rotated counterclockwise to reflect control possibilities.

A social optimum is reached when the global marginal cost of controlling emissions is equal to the global marginal damage cost, i.e., e^*, but firms will emit e^T tons if emitting is free of charge. The dotted curve in Fig. 1 reflects (hypothetical) marginal control costs for the EU ETS. If there is a quota allowing e^q units to be emitted, it is obvious that the marginal control cost in no way reflects the marginal damage cost. The same holds true for an emission charge (tax) such that e^q units are emitted within the EEA. If economic activity increases, the marginal control cost curve shifts to the right. As a consequence, if there is an emission charge, emissions increases from e^q. If there is a permit system, emissions cannot exceed e^q, regardless of economic activity. Hence, as the economy booms, firms must climb along the marginal control cost curve at e^q (or leave or buy permits from other agents). Two further observations follow. First, one cannot rule out that the permit price would exceed p^* (t^*), i.e., the global marginal damage cost at the global optimum e^*. Second, emissions within the area are too low, less than 5% of global emissions, to enable the area to reach the social optimum e^* on its own.

Suppose that the Commission introduces a cap or an emission charge such that the permit price or the charge is equal to p^* or t^*, assuming that the EEA's emissions still are strictly positive. Because the rest of the world emit too much, the EEA permit price or emission charge will not reflect the *actual* marginal damage cost: conditional on actual global emissions. It follows that the permit price or an emission tax does not reflect the present value damage caused by the marginal pollutant, in general. The permit price as well as the tax reflects the wedge between the willingness to pay for a good and the real marginal cost of producing the good. In other words, the permit price reflects the value of the production that the permit allows in its best alternative use. Another interpretation is as follows. A firm acquiring an additional permit avoids marginal control costs. For a profit maximizing (or cost-minimizing) firm, these costs are equal to the permit price (the emission charge). Hence, in general, a permit price or an emission charge lack any obvious interpretation in terms of environmental damage. As hinted at above, the exception occurs if the global emission quota (or the global emission charge) is set at its optimal level, i.e., at e^* in Fig. 1. Then the global marginal control cost and hence the global permit price (or the global emission charge) reflects the marginal damage cost. If the marginal damage curve becomes vertical to the left of the actual emission level, disaster follows (environmental costs become infinitely high) regardless of whether charges or permits or some other policy instrument is used (and designed such that “to much” is emitted). However, the risk of facing such a disaster is smaller under a permit system as emissions are fixed, while their upper bound is unlimited under an emission charge. Therefore, a risk averse (global) government may prefer a permit system to a tax system. For analysis of the impact of uncertainty, refer to Weitzman (1974), Newell and Pizer (2003), and Quirion (2010).

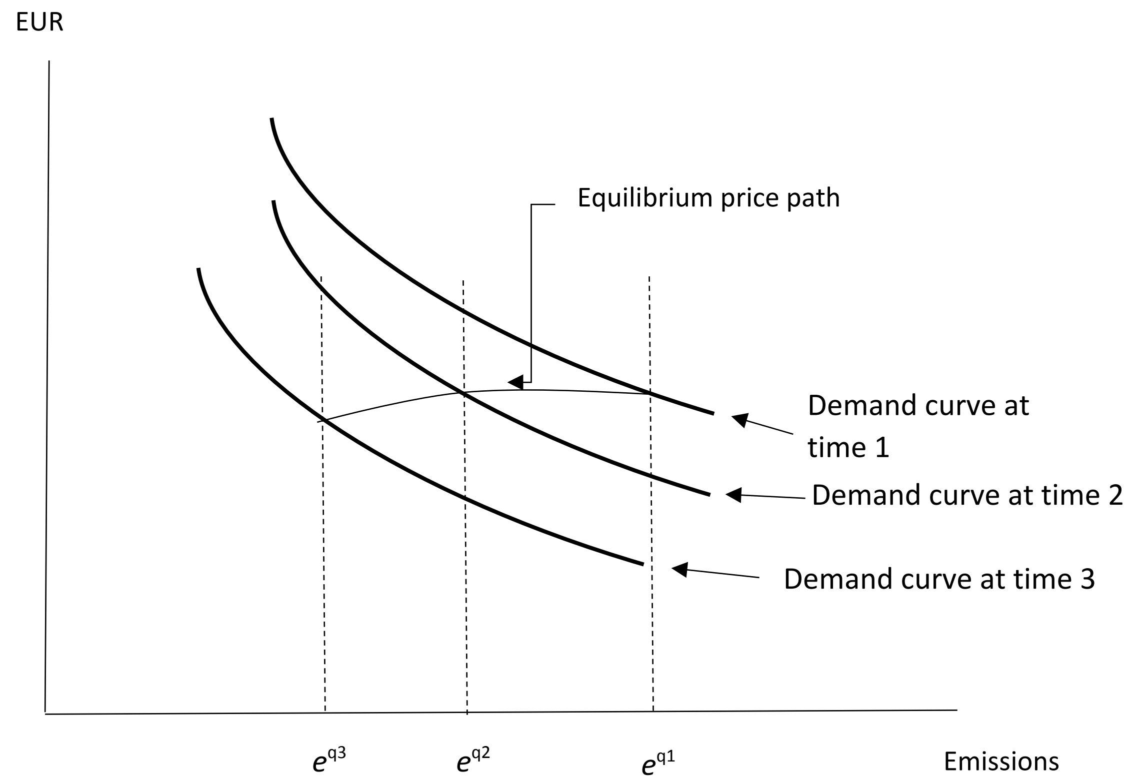

Fig. 2. Illustration of a possible equilibrium price path when both the supply of and demand for permits change over time.

The role of the permit price (within the EEA) is further illustrated in Fig. 2. Now, the number of permits is reduced over time. However, in the figure also demand for permits decreases over time, for example, due to the introduction of cheaper and cheaper clean or control technologies or the relocation of energy-intensive industries to other parts of the world. Thus, over time, permits face fiercer competition. In order to clear the market the permit price may have to fall over certain time intervals. This makes it quite obvious that the role of the permit price is to clear the market, not to reflect the marginal damage cost.

The question arises whether a low equilibrium price is to be preferred to a high one for the same level of emissions? From a welfare point of view, at least, it is hard to say. A lower permit price should lower the prices of products that use fossil fuels as inputs. In turn, purchasers of these products benefit from having to pay less without having to pollute more. On the other hand, a high permit price may indicate that the economy is booming with high economic growth in the area and low rates of unemployment.

3. Permits in cost–benefit analysis

In order to generate cost–benefit rules there must be an activity, either in the private sector or in the public sector that, at least for a hypothetical evaluation, is exogenous. Changing a parameter marginally induces changes in supplies and demand. Working through the general equilibrium effects and evaluating the welfare consequences is the essence of cost–benefit analysis. Here we consider the provision of a public good, interpreted as a shortcut for infrastructure. This good is produced using two inputs: a fossil fuel and a fossil free input, as two inputs are sufficient in the present context. In order to focus on the emissions issue, the cost–benefit analysis evaluates a marginal change in the provision of the public good. There are two scenarios with respect to the fossil fuel. In the first scenario there is a cap-and-trade system. In the second scenario, considered in Section 4, the permit system is replaced by a unit tax on the fossil fuel. In order to focus on how to handle permits and emission charges, there are no other market distortions than the externality in this simple model economy.

Consider the handling of a binding permit system in cost–benefit analysis of a marginal project.

- Value an increase (decrease) in the provision of the public good at the aggregate willingness-to-pay (willingness-to-accept compensation).
- Value all inputs including permits at initial prices.
- The project has no impact on total emissions of greenhouse gases within the EU ETS.
- If the project has an impact on emissions outside the EU ETS, value the impact using an estimate of the global marginal damage cost.

Refer to equation (A.10) for this rule. The simple reason behind this evaluation rule is that total emissions within the EU ETS remain unchanged as long as the quota is binding, i.e., the permit price is strictly positive. The value of a zero change in emissions is obviously also zero.

However, the project may impact on emissions outside the permit system. The following are examples of how such impacts may occur.

- The project may displace a competitor not covered by a cap-and-trade system. This, which may occur inside or outside the EEA, reduces global emissions.
- The project may impact on the global harvest of coal, natural gas, or oil, and the *extraction* of these fuels may generate emissions of greenhouse gases

The permits acquired by the considered activity will displace the production of valued commodities elsewhere in the economy. The permit price reflects the difference between the WTP for the displaced goods less the real marginal cost for the inputs needed for their production. A similar interpretation applies in the case where the provision of the public good is reduced. There is no obvious interpretation of the permit price in terms of damage costs caused by greenhouse gases. As Fig. 1 reveals, the exception is the case where the global quota is at its optimal level e^* where marginal damage costs equal marginal control costs.

The fact that the permit price has no obvious welfare interpretation does not mean that it lacks importance. Its path over time matters.

- The present value permit price path should reflect the expected price path of permits over time.
- The considered project has no impact on the *path* of total emissions within the EU ETS.

Refer to equation (A.13) for a formal rule.

Because the permit price is flexible and determined in a spot market, this case differs from the case where the price of an input is *sticky* and there is either excess supply (unemployment) or excess demand (rationing). In the latter cases it is legitimate to work with a shadow price of the input, a shadow price that might change over time.

One could add a (strictly convex) cost function reflecting the cost of controlling emissions. In this case, a cost-minimizing agent will choose to control in such a way that the marginal control cost equals the permit price or the emission charge. That is, control as long as it is cheaper than purchasing permits or paying the charge. When equality is reached, switch to permits (assuming that the permit price is treated as exogenous by the agent) or paying the charge. Adding a control cost function will not alter the basic result of this paper; refer to the discussion following equation (A.11). What happens is simply that the equilibrium permit price is reduced because there is now a competing technology for the handling of emissions.

The introduction of a control function could be seen as another way of shifting to clean technologies, and with *no impact* on total emissions in a tradable permit system. Obviously, in a cost–benefit analysis, (the change in) control costs must be included as one particular item. In the non-marginal change case, the full marginal cost of abatement includes not only the added technological costs of reducing emissions but also the profit foregone; refer to Montgomery (1972). However, due to envelope properties, the profit change term vanishes for marginal projects, as is illustrated by equation (A.8).

The above cost—benefit rules refer to marginal or small projects. The reader is referred to equations (B.1) and (B.2) for a cost—benefit rule for the non-marginal case where the project is so large that prices are significantly affected. One possibility is to value permits as an area below a curve reflecting the value of the marginal product of the private sector between its initial and final levels of a composite input consisting of permits plus the fuel. In the marginal case this area reduces to a point estimate, neatly illustrating the interpretation of a permit price.

Another factor that could alter the main small project result of this section is market power. Appendix C is devoted to a brief discussion of how the presence of a dominant firm in the permit market may affect the cost–benefit rule. In some cases, the results reported here continue to be valid, but in other cases it is necessary to work with a shadow price.

Finally, consider a capped *output*. This could be a cap on the total annual fish catch. The total annual catch quota is divided into smaller individual portions, each corresponding to a permit. Fishing vessel owners can sell their permits or buy others' permits. Because total output is capped, if a firm is able to increase its market share, it must be at the expense of another producer. Hence, a cost–benefit analysis will reflect changes in production costs and emissions due to any difference in input mixes.

4. Emission charges in cost–benefit analysis

Let us now turn to emission charges. The focus is on a unit tax, but not much is altered if the tax is based on the value of the input, i.e., is *ad valorem*. When there is an emission charge, the cost–benefit rule for a change in the provision of the public good is as follows.

- Value an increase (decrease) in the provision of the public good at the aggregate willingness-to-pay (willingness-to-accept compensation).
- Value all inputs at initial market prices net of taxes.

- Use an estimate of the global marginal damage cost caused by greenhouse emissions to value the increase (decrease) in such emissions.

Refer to equation (A.15) for this rule. The change in tax revenue sums to zero in the cost–benefit rule; a government (or a family) cannot earn revenue by taxing its own activities (family members). This fact explains that inputs are valued net of the tax.

However, there is a caveat. If the price of the taxed fossil energy (or any other price) changes, the private sector's demand for the fuel will also change, and this change will affect the government's tax revenue. In fact, there is a special case that deserves to be mentioned. Suppose the supply of the considered input is completely inelastic, i.e., the supply curve is vertical. Then the following cost–benefit rule applies.

- If supply of the input is completely inelastic, then evaluate the change in the same way as permits.

Thus, in this case there is no impact on the environment; emissions are just "reallocated" from the public to the private sector or vice versa. One way to interpret this case is to assume that a country has imposed a binding target on its emissions of greenhouse gases. The tax is adjusted over time so as to achieve this target, i.e., becomes endogenous. This is the way the UK Green Book handles "non-traded" UK emissions, i.e., emissions from sectors not included in the EU ETS. Refer to UK Government (2009, p. 26).

In any case, in general the major difference between the charge and the permit is that the former has a direct impact on emissions; emissions are endogenous under an emission charge (unless supply of the input is completely inelastic) while they are exogenous under a permit system. If private sector emissions change, this has to be accounted for in valuing the damage cost. Similarly, production possibilities may be affected by changes in emissions.

There is no obvious relationship between the magnitude of the emissions charge and the marginal damage cost caused by emissions. The tax may be higher or lower than the marginal damage cost. Therefore, the charge is no obvious candidate in estimating the costs of greenhouse gases. The only exception occurs when the charge is set at its optimal level; refer to Fig. 1. Then the charge can be used to value the damage caused by emissions, i.e., the externality is internalized. Consider next the case where the tax is changed.

- If the emission tax is changed over time, private sector emissions and hence the stock of emissions is affected. This may affect the *value* of the reduction in emissions achieved by the considered activity.

A project within the EEA may affect firms in other parts of the world, for example, by displacing their production and hence most likely their emissions. The project may also impact on the global harvest of coal, natural gas, or oil, and the harvest of these fuels may generate emissions of greenhouse gases; refer to Section 3. Ideally, such induced effects on global damage costs of emissions are accounted for in a cost–benefit analysis.

5. Conclusions and policy implications

The permit price reflects the difference between the marginal purchaser's marginal revenue and marginal cost of producing slightly more (exclusive of the permit price). In order to maintain equilibrium in the permit market, the permit price must vary over the business cycle. During the boom the demand for permits is high and the price must be high in order to clear the market. During a recession the price must be low in order for demand to match the fixed supply of permits. The role of the permit price simply is to create equilibrium in the permit market. Thus, the permit price does not and should not reflect the marginal damage cost of emissions (unless the cap happens to be set at a social optimum). Hence, it does not make sense to compare the permit price and an optimal emission charge. They simply reflect different issues, except at a social optimum.

Turning to policy recommendations, the cost–benefit rules derived in this paper suggest that permits used up by the (small) project under evaluation should be valued at the ruling permit price. Similarly, if the project switches from a fossil fuel to a fossil-free input, the saved permits should be valued at the ruling permit price. Neither project has any impact on total emissions within the EU ETS. Nevertheless, sometimes a project is presented in such a way that it seems to affect emissions within the EU ETS. To illustrate, the UK Government (2014, Box 3.4, p. 12) estimates that a particular energy efficiency program saves around 5,000 metric tons of greenhouse gases in 2015; the counterfactual is doing nothing. The value of greenhouse gas (GHG) savings is calculated using a forecast permit price. This is in line with the approach used in this paper. However, it is unfortunate to speak of GHG savings. The saved 5,000 permits (one per ton) will be purchased by another firm within the EU ETS, and allows that firm to increase its production by so much that its emissions of GHG increases by 5,000 tons. Hence, the net impact on emissions within the system is zero; -5,000 + 5,000 = 0, i.e., zero emissions footprint.

If the counterfactual is a measure saving 1,000 permits (instead of doing nothing), another firm would purchase the released permits and expand its emissions by 1,000 tons, i.e., also in the counterfactual total emissions remain unchanged. In the cost–benefit analysis of the considered project, value the 4,000 permits (5,000 – 1,000) at the relevant present value permit price. The resulting amount of money reflects the net value of permit-requiring production the project makes possible elsewhere in the area (while the change in emissions of GHG within the area equals zero); value other items, including the fossil fuel(s), in the way stated in Section 3.

The fact that permits should be valued at the permit price implies that it would be a mistake to value permits at the global marginal damage cost or to consider permits as pure transfers, as is done by some leading cost–benefit manuals. Such valuation approaches could cause serious misallocation of scarce resources.

A project may affect emissions outside the EU ETS, for example, by displacing a producer in another geographical area. Then it is reasonable to value the change in emission at the global marginal damage cost. This assumes that the change occurs in a country without a cap-and-trade system or other appropriate policy instruments. To the best of my knowledge, the only manual that addresses this issue is the UK Green Book. It values overseas emissions at a permit price if they occur in a country lacking appropriate carbon pricing arrangements; refer to UK Government (2014, p. 14). This may be a reasonable compromise in the likely case where it is only known that a project displaces (or causes) emissions outside the EU ETS.

A public sector program may be so large that it has a significant impact on the permit price, and possibly also on other relative prices. This case is briefly considered in equations (B.1) and (B.2) in Appendix B. A possibility is to value permits as an area under an inverse demand function for private sector permits between its initial and final permit levels. This yields an area reflecting the value of the marginal product the private sector loses as it is displaced in the permit market; in the marginal case the permit price can be interpreted as the value of the marginal product of permits evaluated at a "point".

If there are firms that are so large that they exercise market power in the permit market, it may be necessary to work with a shadow price instead of the permit price; refer to Appendix C. A dominant firm will under-abate (or over-abate) and over-purchase (under-purchase) permits and thus drive up (down) the permit price. If the considered small project displaces a dominant firm in the permit market there is an extra societal cost (gain) not reflected by the permit price. Hintermann (2015) suggests that market power is likely to be an empirically relevant concern during the early years of an emission permit market. As the EU ETS and the Union's internal energy market mature, as they do according to Aatola (2013), the market power issue may be of less significance; thus far, no direct tests of market power exist in the context of the EU ETS, mainly due to data limitations.

Hintermann et al. (2014, p. 21) conclude that it is unclear “whether or not the price signal provided by the carbon market is approximately right, or whether there is some deviation that would have to be explained by issues such as transactions costs, high aversion to engaging in risky abatement decisions under uncertainty or imperfect competition.” On the other hand, Aatola (2013, p. 6) concludes that “Carbon [within the EU ETS] has a price that reflects to a large extent the market fundamentals in the study period [2005-2011]. The markets are maturing even if not fully informational efficient yet.”(See also Aatola et al. (2013), and Okullo (2012) for a summary of other empirical studies of signs of market power within the EU ETS.) The remaining question is how to estimate whether the term in equation (C.3) is large relative to the permit price (i.e., important/significant), and how to determine to what extent, if any, the dominant firm is affected by the considered public sector project.

Appendix A. Technical details: Model and CBA rules

In this appendix a simple model is used to further illustrate the cost–benefit rules presented in the main text of this paper. In order to focus on the treatment of permits and charges, distributional issues are set aside. Therefore, there is just a single, representative household. This household is equipped with the following indirect utility function, which also acts as the social welfare function:

$$V = V(\mathbf{P}, y, z, G), \tag{A.1}$$

where **P** is a vector of commodity prices, *y* is lump-sum income, *z* is a public good, say, infrastructure, and *G* represents the welfare impact of greenhouse gases. Let us consider a kind of aggregate private sector that needs permits. In order to arrive at a simple cost–benefit rule, it is initially assumed that the sector has no technology for controlling emissions, but this assumption is abandoned later on. The sector is modeled in the following simple manner:

$$\pi = p^x \cdot f(r, e, G) - p^r \cdot r - p^e \cdot e - P \cdot g(e) + P \cdot \bar{X}, \tag{A.2}$$

where p^x is the price of the output, $x = f(.)$ is a well-behaved production function, with $\partial f(.)/\partial G = f_G(.) \gtreqless 0$, as some parts of the economy may gain from more greenhouse gases while other may lose, p^r is the price of a renewable input, *r* is demand for the renewable input, p^e is the price of the single fossil fuel, *e* is demand for the fossil fuel, *p* is the permit price per ton emitted, $em = g(e)$ is the number of tons of greenhouse gases emitted as a function of the number of tons of fossil fuel the sector uses, and $\bar{X}$ is the lump-sum allocation or grandfathering of permits to the sector. For notational simplicity $\bar{X}$ is set equal to zero in what follows. It seems legitimate to assume that the emission factor, i.e., $g_e(.)$, where a subscript refers to a derivative with respect to *e*, is constant (but varies across different fossil fuels, as is discussed in, for example, Australian Government (2014)). Therefore, one can rescale the permit price such that $P = (g_e^{-1}) \cdot p$, and write the permit cost as $p \cdot e(.)$.[1] Assuming that the sector treats all prices as exogenous, profit maximization will result in a profit function:

$$\pi(p^x, p^r, p^e, p, G) \equiv p^x \cdot x(p^x, p^r, p^e, p, G) - p^r \cdot r(p^x, p^r, p^e, p, G) - (p^e + p) \cdot e(p^x, p^r, p^e, p, G). \tag{A.3}$$

In these functions *p* and p^e appear as separate arguments but one could as well merge them to a single argument $p + p^e$. The sector may use other resources as inputs, but they are not needed in the analysis to follow and hence they are suppressed. For the same reason, all other private firms in this model economy are suppressed. There are also firms producing the inputs. By assuming that the

[1] Set $g_e = \alpha$. Then $P \cdot e^m = P \cdot \alpha \cdot e = p \cdot \alpha^{-1} \cdot \alpha \cdot e = p \cdot e$.

price of the fossil fuel is determined in world markets we can abstain from modeling the supply. The renewable input is simply harvested without needing any variable inputs. The profits of the representative producer is $\pi^r(p^r) = p^r \cdot r^s$, ignoring any impact on harvesting of greenhouse gases.

The public sector is modeled in the following simple way:

$$T = p \cdot e^q - (p^e + p) \cdot e^z - p^r \cdot r^z, \tag{A.4}$$

where T is a lump-sum payment/tax, e^q is the fixed number of permits, and the public sector uses the fossil fuel, denoted e^z, and the renewable input, denoted r^z to produce the public good, which is provided free of charge.

Finally, lump-sum income y in the social welfare function (A.1) has the following components:

$$y \equiv \pi(p^x, p^r, p^e, p, G) + \pi^r(p^r) + T, \tag{A.5}$$

where profits by other private firms than the considered sector are suppressed. The representative household is assumed to treat all prices as well as profit income as fixed, although (some or all relative) prices, and hence also profits, are endogenous from the point of view of the economy.

An equilibrium in the permit market is reached when the permit price is such that:

$$e(p; p^x, p^r, p^e, G) + e^z = e^q, \tag{A.6}$$

where the emission factor g_e is used to convert the exogenous number of permits to fuel units. The price p is such that total demand for permits equals the issued number of permits within the EEA, i.e., e^q, holding all other prices and emissions constant.

Emissions accumulate in the atmosphere if the stock is above the environment's assimilative capacity. In economics, the stock of emissions often is modeled as following a differential equation:

$$\dot{G}(t) = e^R(t) + e^q(t) - \alpha \cdot G(t), \tag{A.7}$$

where $G(t)$ is the accumulated stock of emissions at time t, a dot refers to a time derivative, $e^R(.)$ is the rest of worldwide time t emissions, and the parameter α captures the environment's assimilative capacity. Provided global emissions, $e^W = e^q + e^R$, remain constant over time, the stock will reach a steady state equal to $\overline{G} = e^W / \alpha$. In what follows, any time pattern is suppressed, and focus is on current emissions under a permit system, as in equation (A.6), or emissions from the EEA under an emission charge. This simplification, which avoids introducing quite complex integrals, has no impact on the qualitative results presented in this paper.

Let us now introduce a marginal policy change by the public sector. Marginal policy changes or projects are the backbones of cost–benefit rules found in the literature. Even small projects typically influence general equilibrium prices. As a first step let us consider the impact on social welfare of marginal changes in the input prices:

$$
\begin{aligned}
\frac{\partial V}{\partial p} &= \frac{\partial V(.)}{\partial y}[\frac{\partial \pi(.)}{\partial p}+\frac{\partial T}{\partial p}] = V_y(.)\cdot[-e(.)+(e^q-e^z)] \\
\frac{\partial V}{\partial p^r} &= \frac{\partial V(.)}{\partial y}[\frac{\partial \pi^r(.)}{\partial p^r}+\frac{\partial \pi}{\partial p^r}+\frac{\partial T}{\partial p^r}] = V_y(.)\cdot[r^s(.)-r(.)-r^z]
\end{aligned}
\tag{A.8}
$$

where $\partial V(.)/\partial y = V_y(.)$ is the marginal utility of income, and the (unconstrained) envelope theorem has been employed to arrive at these results; refer to, for example, Silberberg and Suen (2001, Ch. 7), Johansson and Kriström (2015, pp. 11-12), and Simon and Blume (1994, Theorem 19.4). If no other firms are affected by these price changes, both expressions are equal to zero, because prices clear markets. (If other firms are affected by the change in p or p^r, add the corresponding demand/supply functions.) Consider next a small change dz in the provision of the public good accompanied by changes in the amounts of inputs used:

$$
\begin{aligned}
dV = &\; V_z(.)dz + V_y(.)[\frac{\partial \pi(.)}{\partial p^r}dp^r + \frac{\partial \pi(.)}{\partial p}dp + \frac{\partial \pi^r(.)}{\partial p^r}dp^r + dT] \\
&+ [V_y(.)\frac{\partial \pi(.)}{\partial G} + \frac{\partial V(.)}{\partial G}]de^R \\
= &\; V_z(.)dz - V_y(.)[(p+p^e)de^z + p^r dr^z] \\
&+ [V_y(.)p^x \cdot f_G(.) + V_G(.)]de^R,
\end{aligned}
\tag{A.9}
$$

where $V_z(.) = \partial V(.)/\partial z$ is the marginal utility of the public good, $\partial \pi(.)/\partial G = p^x \cdot f_G(.)$ is the value of the marginal product gained/lost as emissions of greenhouse gases change marginally, $\partial V(.)/\partial G = V_G(.)$ is the marginal disutility of greenhouse gases, $dG = de^R \gtreqless 0$, while $de^q = de + de^z = 0$, and equation (A.8) has been used to simplify the equation. Note that p, p^r, T, and G are endogenous, implying that $dp = (\partial p/\partial z)dz$ and similarly for the other items (and the input levels are determined by the production function); they are "driven" by the parameter z. As illustrated by equation (A.8), if prices clear markets, r^s equals demand for the renewable input while e^q equals demand for permits (ignoring here demand by other sectors than the two under scrutinization). Hence, these terms are equal to zero, explaining that only the utility value of the change in z and the utility value of the change in the public sector's production cost (valued at initial prices) remains in the final line of equation (A.9). The market equilibrium assumption can be used to handle any marginal adjustments the considered project causes elsewhere in the economy. Thus the rule derived here is quite general.

Multiplying through by the inverse of the marginal utility of lump-sum income, i.e., $1/V_y(.)$, converts the expression from units of utility to monetary units. Then, one has a simple *general equilibrium* cost–benefit analysis of the considered marginal project:

$$\frac{dV}{V_y(.)} = \frac{V_z(.)}{V_y(.)}dz - [(p + p^e)de^z + p^r dr^z] + [p^x \cdot f_G(.) + \frac{V_G(.)}{V_y(.)}]de^R. \quad \text{(A.10)}$$

Note that the change in (unobservable) units of utility is proportional to the monetary outcome, as the "exchange rate" between units of utility and monetary units, $V_y(.)$ is evaluated at a "point". Thus the shift is socially profitable if the willingness-to-pay for the extra units of the public good at least cover the cost of acquiring the needed inputs (for the moment holding emissions constant). The cost–benefit rule in (A.10) highlights that emission permits are treated as any other input.

Total emissions of greenhouse gases within the EU ETS remain unchanged: the permits that are acquired for the production of the public good will displace emissions elsewhere in the economy. When a project affects emissions in the rest of the world, i.e., $dG = de^R \neq 0$ in equation (A.10), then the associated (positive or negative, depending on the direction of the impact) WTP must be accounted for; both profit income, i.e., $p^x \cdot f_G$ (.), and household willingness-to-pay, as captured by $V_G(.)/V_y(.)$, must be accounted for if $de^R \neq 0$.

Note that if we consider the permits used by the public sector as a transfer within the public sector, nothing is changed. The actual revenue from permits is equal to $p \cdot e(.)$, because the government cannot earn revenue by selling to itself, but $de = -de^z$ because the number of permits is fixed. Therefore, according to this approach too, there is a cost or loss of permit revenue equal to $-p \cdot de^z$ when the public sector acquires de^z additional permits (plus the fuel cost). This establishes the desired result.

Thus far, the possibility to control emissions has been ignored. It is straightforward to add a cost control function $c(e^c)$, where ec^c is the quantity of emissions controlled, to equation (A.2). Next, modify the cost of acquiring permits to read $p \cdot (e - e^c)$. Then equation (A.2) is modified as follows:

$$\pi^c = p^x \cdot x - p^r \cdot r - p^e \cdot e - p \cdot (e - e^c) - c(e^c). \quad \text{(A.11)}$$

An interior solution requires that $c_{e^c}(.) = p$, i.e., control to the point where the marginal control cost $c_{e^c}(.)$ is equal to the permit price *p*, then turn to purchasing permits. Basically, the introduction of a control function causes a counterclockwise rotation in the demand curve (around the level emitted when p = 0). The cost–benefit rule in equation (A.10) is augmented by the negative of the marginal control cost, i.e., $-c_{e^c}(.)de^c$, which equals $-pde^c$. (The term is added to the cost–benefit rule because the public sector's revenue from selling permits now is $p \cdot (e - ec)$.)

Consider next a marginal *ceteris paribus* reduction in e^q, with $dz = de^R = 0$. The cost–benefit rule of such a reduction reads:

$$\frac{dV}{V_y(.)} = [p + p^x \cdot x_{e^q}(.) + \frac{V_G(.)}{V_y(.)}] \cdot de^q. \tag{A.12}$$

The first term within brackets represents a loss of permit revenue (reflecting a loss of production in the economy). The second term is a change in profit income as production possibilities are affected by less emissions. The final term within brackets is the representative household's WTP for slightly less greenhouse gases. Society gains from reducing emissions as long as the WTP for an additional permit, i.e., the permit price, is lower than the marginal WTP for less emissions of greenhouse gases, including the change in profit income; the WTP for a change in profit income equals the change in profit income. The dynamic consequences, as captured by equation (A.7), are ignored here. (If the representative household is a pure altruist it will account for damages it causes to others, irrespective of where they live. Alternatively, one may look at a global representative household when analyzing the impact of changes in emissions.) Refer to Tol (2012) for an analysis along these lines of the European Commission's 2020 climate package.

Returning to our project, let us now suppose that there are two periods. In the second period, the number of permits is reduced from e^q to e^{q*}. This causes the (current value) permit price to increase from p to p^*. Then the present value cost–benefit rule reads:

$$\begin{aligned}\frac{dV}{V_y(.)} = & \left(\frac{V_z(.)}{V_y(.)} + \frac{V_{z_2}(.)}{V_y(.)}\right) dz - [(p + p^e)de^z + p^r dr^z] \\ & - \frac{[(p^* + p^e)de_2^z + p^r dr_2^z]}{1+i} \\ & + \left(p^x \cdot x_{e^q}(.) + \frac{p^x \cdot x_{e^q}(.)}{(1+i)} + \frac{V_G(.)}{V_y(.)} + \frac{V_{G_2}(.)}{V_y(.)}\right) de^R,\end{aligned} \tag{A.13}$$

where i is the discount rate, $V_{z_2}(.)$ ($V_{G_2}(.)$) is the second-period marginal utility of the public good (second period marginal disutility of emissions) as seen from (or discounted to) the beginning of the first period, $V_y(.)$ is the marginal utility of a present value EUR, dz, de^R and all current value prices but the permit price for notational simplicity are kept constant across time (while the input mix may change due to the change in relative prices), and the reduction in permits occurs independently of the project under evaluation.

One could also interpret prices and quantity changes in equation (A.10) as vectors with individual prices interpreted as present values at different points in time, and z, de^z and dr^z as transposed row vectors, and $V_y(.)$, $V_z(.)$, and $V_G(.)$ interpreted as in equation (A.13). In such a case, with banking and borrowing allowed, the permit price increases at the discount rate, i.e., the present value permit price remains constant (Hotelling's rule). Then the market is arbitrage-free; an interior solution requires that investing in permits (or controlling emissions) and investing in the other asset (money) yields the same return. More complicated price paths may result, for example, if the number of permits is changed over time, as in equation (A.13), or if banking and/or borrowing is either restricted or even prohibited. However, one can proceed as in equation (A.13), i.e., value permits at forecast present value prices, as long as the price path is exogenous to the considered project and the project is small or marginal (so that one can draw on envelope properties).

Another issue to address is the interpretation of the permit price. A necessary condition for profit maximization is that $p = p^x \cdot f_e(p^x, p, p^e, p^r, G) - p^e$, i.e., the permit price equals the value of the marginal product of the fossil fuel less the fuel price. Using this result in equation (A.10), it is easily verified that one can replace the term $(p^0 + p) \cdot de^z$ by the value of the marginal product lost in the private sector as it is displaced by the considered project. This illustrates that the permit price does not reflect the marginal damage cost, unless the global quota is at its optimal level. In addition, from equation (A.8) it follows that the permit price should balance supply of and demand for permits.

Consider finally a unit tax on emissions (and no permit system). The government's budget constraint is now:

$$T = t \cdot e(.) - p^r \cdot r^z - p^e \cdot e^z, \tag{A.14}$$

where t is the unit tax, and $e(.)$ is the private sector's demand function for the fossil fuel. Proceeding as in equation (A.9), the cost–benefit rule reads:

$$\begin{aligned} \frac{dV}{V_y(.)} = \; & \frac{V_z(.)}{V_y(.)} dz - [p^e de^z + p^r dr^z - t \cdot de(.)] \\ & + [p^x \cdot f_G(.) + \frac{V_G(.)}{V_y(.)}](de + de^z + de^R). \end{aligned} \tag{A.15}$$

Note that there is a tax change term, $t \cdot de$. Thus the usual partial equilibrium result is only valid if all relative prices affecting (in this simple case) the private sector's demand function for emissions remain unchanged. Also note that any change in *e*(.) will affect the damage caused by emissions; in addition, a project may also impact on emissions e^R from the rest of the world. As emissions increase, the final term within brackets in equation (A.15) can be interpreted as the marginal willingness-to-accept compensation in lieu of more emissions. Thus, the WTP for more of the public good must not only cover its own costs adjusted for the impact on tax revenue but also the net impact on global marginal damage costs.

If the supply of the fossil input is completely inelastic, then $de = -de^z$, and the shift is evaluated in the same way as permits. In particular, total emissions within the EEA remain unchanged: $de + de^z = 0$.

Appendix B. Large projects

Let us also briefly consider a discrete or non-marginal increase in the provision of the public good. Suppose that this causes at least *p*, but possibly also other (relative) prices in equation (A.5), to change from their initial general equilibrium levels to new general equilibrium levels, but for simplicity global emissions remain constant. The WTP for the change, denoted *CV*, is implicitly defined by the following equation:

$$V(\mathbf{P}, y^1 - CV, z^1, e^q + e^R) = V(\mathbf{P}, y^0, z^0, e^q + e^R), \tag{B.1}$$

where a superscript 0 (1) refers to initial (final) or pre-project (post-project) levels, $CV = \Delta\pi + \Delta\pi^s + \Delta T + CV^z$, with $y^1 - y^0 = \Delta y = \Delta\pi + \Delta\pi^s + \Delta T$, and CV^z denoting the WTP for the extra units of the public good. The individual pays (receives compensation) for each positive (negative) change in profit income and the tax so as to throughout remain at the initial level of utility. Thus, the WTP for the change in the provision of the public good is assessed holding lump-sum income at its initial level y^0.

The change in the considered project's permit cost is $\Delta C^p = p^1 \cdot e^{z^1} - p^0 \cdot e^{z^0}$, where in the simplest case $e^{z^0} = 0$. This change can also be stated in terms of the change in the government's permit revenue C^g, i.e., $\Delta C^g = (p^1 \cdot e^1 - p^0 \cdot e^0) = \Delta C^p$, because the government cannot earn revenue by charging public sector projects. However, in contrast to a reasonably small project where $p^1 \approx p^0$, $\Delta C^p \approx p^0 \cdot \Delta e^z$, and equation (A.8) can be used to eliminate profit change terms, in the non-marginal case one must account for changes in profit incomes.

There are several different ways in which the different terms can be aggregated. For simplicity, assume that only the permit price changes significantly. Then, one way of aggregating is as follows:

$$\begin{aligned} \frac{\Delta V}{\overline{V}_y} &= CV^z - p^r \cdot \Delta r^z - (p^1 + p^e) \cdot e^{z^1} + \Delta p \cdot e^q - \int_{p^0}^{p^1} e(p^x, p, p^r, p^e, G)dp \\ &= CV^z - p^r \cdot \Delta r^z + \int_{e^0}^{e^1} h(e, p^x, p^r, G)de, \end{aligned} \tag{B.2}$$

where $\overline{V}_y$ is the marginal utility of income evaluated at some intermediate income level[2], the counterfactual requires zero permits (doing nothing) , and *h*(.) is the inverse demand function for the

[2] $\Delta V = V(\mathbf{P}, y^1, z^1, e^q + e^R) - V(\mathbf{P}, y^1 - CV, z^1, e^q + e^R) = \overline{V}_y \cdot CV$, where, drawing on the intermediate value theorem, the marginal utility of income is evaluated at an income $m \in [y^0, y^1]$.

composite input composed of the fossil fuel and permits. The last but final term in the middle equation yields the *gross* gain in public sector revenue as the permit price increases, i.e., ignoring that some of the permits are sold to a public sector project. The final term in the middle equation represents the loss in producer surplus or profits as the permit price increases, i.e., the area to the left of the demand curve for permits between initial and final permit prices. Taken together, these two terms in the middle equation plus the project's cost for permits and the fossil fuel corresponds to the area below the private sector's inverse demand function for the composite input between initial ($e^0 = e^q$) and final (e^1) levels for e. This area, captured by the final integral in equation (B.2), yields the value of the marginal product lost (along the optimal path) as the sector is displaced. Thus the area is the negative of the total WTP of having e^0 rather than e^1 units of the composite commodity. This is illustrated in Figure 3.

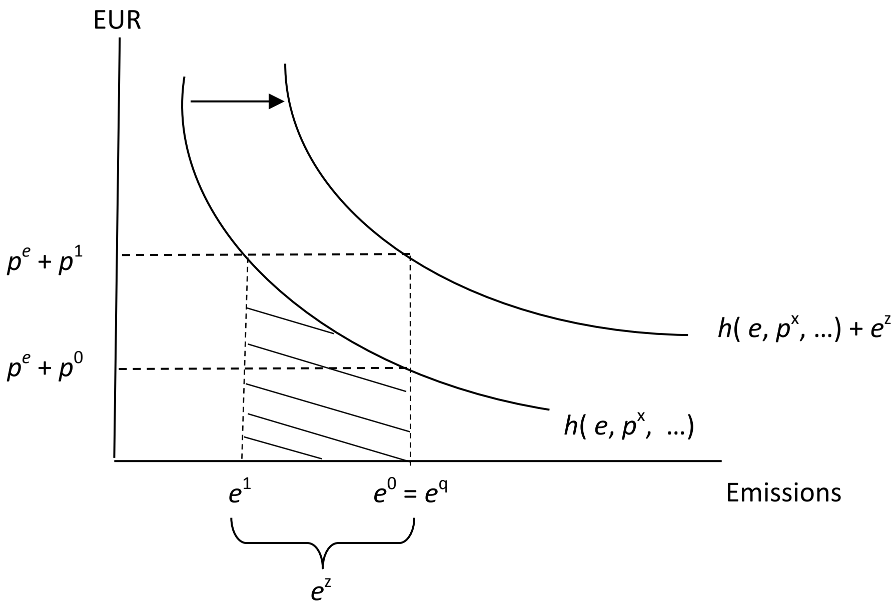

Fig. 3. The social cost of employing more of the composite input (fossil fuel plus permits).

Appendix C. On market power in emission markets

This brief appendix introduces market power in the permit market. There are a number of fringe firms that act as price takers, just as the firm in equation (A.11). There is a single dominant firm. Its profits are defined as follows:

$$\pi_1 = p^x \cdot x_1 - w \cdot l_1 - p^e \cdot e_1 - p \cdot (e_1 - e^c) - c(e^c) + p \cdot \overline{e}_1, \tag{C.1}$$

where the subscript 1 refers to the dominant firm, and $\overline{e}_1$ is the free allocation of permits. Differentiating this expression with respect to gross emissions e_1 and the amount of emissions controlled e^c yields:

$$(p^x \cdot f_{e_1} - p^e - p)de_1 - (e_1 - e^c - \overline{e}_1)\frac{\partial p}{\partial e_1}de_1 + (p - c_{e^c})de^c, \tag{C.2}$$

where, by assumption, $de_1 = -de^z$. If the firm has no market power, then $\partial p/\partial e_1 = 0$ and the first expression within parentheses is equal to zero (the value of the marginal product equals the combined input price), and the marginal abatement cost is equal to the permit price. This is the case considered in Appendix A.

Suppose next that the firm has market power, i.e., that $\partial p/\partial e_1 > 0$. Then it chooses to purchase permits in such a quantity that equation (C.2) is equal to zero. Depending on the free allocation $\overline{e}_1$ it receives and its influence on the permit price, the firm may either under-abate and overbuy permits ($p > c_{e_c}(.)$) and thus drive up the permit price, or over-abate and underbuy permits ($p < c_{e_c}(.)$) and thus drive down the price, relative to the efficient solution; refer to Hintermann (2013, p.5). However, note that with full free allocation of permits, efficiency is achieved. This classic result was derived by Hahn (1984). However, if the output price is correlated with the dominant firm's purchases of permits, i.e., $\partial p^x/\partial e_1 > 0$, Hahn's result is invalidated; refer to Hintermann (2013). Nevertheless, without free full allocation, we would have to add an estimate of the following positive or negative market power (*d*MP) term to the cost–benefit analysis:

$$d\text{MP} = (e_1 - e^c - \overline{e}_1)\frac{\partial p}{\partial e_1}de_1. \tag{C.3}$$

Recall that this is the (positive if $e_1 - e_c > \overline{e}_1$ and $de_1 = -de^z > 0$) difference between the first and final expressions within parentheses in equation (C.2). Even though e_1 is set such that equation (C.2) equals zero, the expression in (C.3) appears in the government's budget (with a positive sign in front of it). It represents the difference between the willingness to pay for an additional unit of the resource and its marginal cost adjusted for the inefficiency in the control cost market ($p \neq c_{e^c}$), multiplied by de_1. This gain (loss if the expression within parentheses in (C.3) is negative) is attributed the project under evaluation while it represents an additional cost if $de^z = -de_1 > 0$ (gain if the expression within parentheses in (C.3) is negative). However, this assumes that the project under evaluation either displaces only the dominant firm (when $de^z > 0$) or that the permits it abstains from purchasing (when $de^z < 0$) all are acquired by the dominant firm.

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