

Chapter 17

Price and quantity regulation for reducing greenhouse gas emissions

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Note: Photos and biographies of co-authors can be found in the appendix.

The challenge of climate change¹

Climate change is a market externality.² Market actors emit greenhouse gases (GHGs), leading to costs in terms of climate change damages that are not paid by the emitters themselves, but by others. The result of this market failure is that more than the optimal level of GHGs is emitted. If the external costs were included in the costs of emitting GHGs ('internalizing the costs'), it would become unprofitable to continue emitting GHGs at the current rate. Internalization of the costs is thus essential for effective long-term reductions in GHG emissions.

Two major types of market instruments have been proposed to internalize the cost of pollution: Pigovian pollution taxes³ (a price signal), and tradable pollution permits (a quantity signal). The idea of Pigovian taxes is to make the polluter pay the external costs of pollution, thus bringing together the social and private costs of polluting, and therefore adjusting pollution to the efficient level. The key difficulty with Pigovian taxes is calculating which level of tax will counterbalance the pollution externality (i.e., calculating the marginal damages⁴ of pollution). In contrast, tradable pollution permits give rise to a price on pollution that reflects the relative scarcity of pollution permits; for example, the quantity of the permits will determine its price. The key difficulty here is in setting the quantity of permits, and thus the overall pollution, to the efficient level. It is a long-standing debate in environmental economics which of the two instruments is superior in varying circumstances (Hepburn, 2006).

Based on the concern that there are tipping points in the Earth's climate system, the triggering of which could dramatically increase climate change damages (and the uncertainty about them), policymakers need to decide to avoid dangerous interference with the climate system (as expressed in Article 2 of the Framework Convention on Climate Change). This decision would most likely involve setting a climate protection target, for example in terms of a maximum temperature rise.

¹ This text focuses on the design of climate policy instruments. It does not derive a global cumulative carbon budget that would allow us to achieve either an optimal temperature goal or an optimal cost-benefit ratio. To do this, questions of ethics, equity and environmental effectiveness would have to be discussed. Within this text we instead assume that these questions have already been resolved by a careful application of welfare economics and ethics. Therefore, we limit our analysis to the design of policy instruments necessary to address the market failures associated with man-made climate change. The results presented here remain valid in a cost-benefit-analysis (CBA) in which the damages are taken into account explicitly. Such a CBA would be one method to derive the optimal carbon budget (for further discussion of this point see Edenhofer and Kalkuhl, 2009).

² A market externality is the impact (positive or negative) of a market transaction on a third party that is not directly involved in the transaction. In terms of climate change, this means that the price paid for energy does not reflect the climate change due to energy production and the resulting damages to all people suffering from climate change.

³ A Pigovian tax is designed to raise a market activity's price to its true costs, including external costs.

⁴ In economics, the term 'marginal' is used to describe the change of an aggregated value associated with the last unit produced or emitted. The marginal cost is the change in total cost that arises when the quantity produced changes by one unit, thus it is the cost of producing one more unit of a good. The marginal damage of carbon dioxide would be the additional damage caused by emitting one additional tonne of carbon dioxide.

Such a target can be converted to a total maximum carbon budget that may be used without incurring an unacceptably high probability of violating the climate protection target (Meinshausen *et al.*, 2009). Once the carbon budget is set, the question remains how to cost-effectively allocate its usage over time.

Moreover, climate protection requires the transformation of the existing energy and transport infrastructure into an energy-efficient, low-carbon infrastructure. This transformation is an ongoing project involving huge long-term investments, for example in low-carbon power plants and the energy-efficient refurbishment of existing buildings. These investments will only occur if stable long-term expectations about the carbon price persist. Research has shown that early investments into efficient energy use and clean technologies can greatly reduce the economic cost of climate protection (Grubb *et al.*, 1995, Edenhofer *et al.*, 2009 b). Therefore, creating stable, long-term expectations about future carbon prices – implemented through either a quantity or price regulation – and designing credible long-term road maps for climate protection are central tasks for policymakers.

Introduction to the debate on price versus quantity instruments

To contribute to the debate about climate change policy instruments, we developed a conceptual computer-based economic model. Before using the model for a detailed analysis of the economic properties of tax and quantity instruments in the subsequent sections, we begin by stating three arguments that cannot be treated in our single-region model because they relate to international concerns:

1. **International harmonization of carbon prices:** Since climate change can only be tackled globally, a meaningful effort will have to rely on the implementation of carbon pricing mechanisms in most regions of the world. It is a clear advantage of emission trading schemes (ETSs) that mechanisms creating (i) an integrated international cap-and-trade system, and (ii) incentives for reducing emissions in regions without an emissions cap (as attempted by the clean development mechanism, CDM) are conceivable. This would lead to the emergence of a globally harmonized carbon price.⁵
2. **International burden sharing:** Another advantage of implementing carbon markets rather than carbon taxes is that international burden sharing of the costs of climate change and emissions abatement can be more easily achieved

⁵Taxes are a policy instrument that most nations and political parties are very sensitive about. The ongoing difficulties encountered in the process of harmonizing taxes among EU countries demonstrate how complicated international tax harmonization would be. Emissions trading systems do not yet carry a similar ideological burden. Therefore, it seems plausible that introducing and linking ETSs will be more feasible. Furthermore, most nations already levy energy taxes, some of them justified by climate change. It is not clear if a harmonized carbon tax would replace or complement existing taxes.

by adjusting regional caps and allowing for interregional trade in permits. Admittedly, the tax revenues could also be recycled to yield the same outcome as ETS burden-sharing schemes. However, the institutional prerequisites might be more demanding for an international tax scheme in which an international body has to be endowed with the power to transfer the tax income from one nation state to another, a mechanism that has proven difficult in the past.

3. **Setting the baseline:**⁶ Closely linked to the question of burden sharing is the question of baseline setting. While all evidence speaks in favour of auctioning permits at a national level, how should permits be distributed between the states participating in an ETS? The possibility of changing this distribution by setting different baselines allows for international burden sharing, but at the same time it creates a very difficult negotiation topic: As it is necessary to set an individual baseline for each country, each country will try to influence the negotiations to increase its own baseline. A tax, by contrast, does not necessarily create this problem. Setting an equal tax without tax exemptions can therefore be appealing due to its simplicity and perceived equal treatment of all parties. Whether this difference is seen as an advantage or disadvantage compared with an ETS depends on the assumptions about the political process leading to an international agreement, and the negotiation position of the different nations involved.

Frameworks to explore price and quantity policies *Cost-benefit analysis versus carbon budget constraint*

The difference between price and quantity instruments has been mostly discussed within a cost-benefit analysis framework. Under such a framework both the economic costs and benefits of a given strategy are evaluated. The difficulty of such an analysis is that it raises many questions about the value of goods that cannot be bought or sold, such as ‘what is the value of clean air?’

Weitzman (1974) has shown within a static framework that price instruments are superior to quantity instruments if marginal abatement costs increase faster than marginal damages. The extension of Weitzman’s famous framework to a stock-pollutant problem such as climate change, in which not the annual emissions themselves but the cumulative stock of all previous emissions produces climate change damages, was undertaken by Newell and Pizer (2003). Under their – quite specific

⁶ A baseline is the amount of emissions against which efforts of countries to decrease GHG emissions are measured. A country with a fast-growing population might have a growing baseline to reflect the fact that it will find reducing total emissions more difficult than a country with decreasing population.

and partly questionable – assumptions,⁷ taxes will usually be preferred in the first periods when marginal damages do not change much as GHG concentrations are still low and severe climate damages are still far away and are therefore reduced through discounting; in later periods marginal damages of emissions rise due to higher GHG concentration and discounting will have less effect. Then, the marginal damages increase faster than marginal mitigation costs and a quantity instrument like an ETS performs better.

In contrast to Weitzman's cost-benefit framework, we do not perform a full cost-benefit analysis. Instead, we assume a given and fixed carbon budget and discuss instruments to achieve this target with minimum costs. Such a framework circumvents the need to estimate an appropriate damage function required for cost-benefit analysis, which would be very difficult because the exact future damages resulting from an incremental amount of emissions are extremely sensitive to future emission paths, climate sensitivity and available technologies (Stern, 2008). Furthermore, other side effects of high carbon dioxide concentrations in the atmosphere, such as ocean acidification, would have to be considered. To complicate the problem, valuation of damages is not possible without normative assumptions about the needs and preferences of future generations. Finally, the Earth system as a whole has a value of its own that exceeds its economically quantifiable value. Hence, we will compare taxes and ETSs in the context of achieving a given cumulated carbon budget ('all nations together may not emit more than a certain amount of carbon dioxide – for example, 1000 gigatonnes carbon dioxide equivalents – over the next few hundred years') at maximum welfare.⁸

Social planner model versus game theory

The debate about prices versus quantities has mostly been discussed within the framework of a social planner. Such a model assumes a benevolent planner with full foresight who takes all decisions. While the social planner framework defines

⁷They allow negative net emissions, assume exponential decrease of abatement costs (the costs associated with reducing emissions), decay of carbon dioxide with a half-life of 84 years (newer scientific research claims a half-life of temperature change of >1000 years, see Matthews and Caldeira, 2008), and set damages from global warming to 1.85% of GDP at 3 °C temperature (a survey among environmental economists estimated the loss at 6.5% GDP at 3 °C temperature increase, see Roughgarden and Schneider, 1999).

⁸Welfare is here calculated as the time-discounted sum of the logarithm of consumption over the next hundred years. While this indicator does not encompass all that is included in the common usage of the term 'welfare', it is one of the main measurements used in economics due to the methodological difficulties of including more complex concepts like 'sustainability' or 'happiness'. Different efforts have been made to create a more holistic indicator for welfare like the Index of Sustainable Welfare (ISEW), the Genuine Progress Indicator (GNI), the Gross National Happiness Product (GNHP) or the Happy Planet Index (HPI). However, these alternative concepts all suffer from limitations (Lawn, 2005) and have not succeeded in replacing purely monetary measures like GDP or consumption.

a benchmark of ‘first best’⁹ solutions, it does not allow the assessment of policy instruments when multiple externalities – such as market imperfections, technological spillovers or incomplete futures markets – require correction.

In contrast, a game theoretic model with different actors who all maximize their own welfare allows the inclusion of market failures and is therefore better suited to the analysis of policy instruments targeting multiple externalities.

General features of our model

To address the above-mentioned concerns, we developed a model with the following main features.¹⁰ First, it is an endogenous growth model; saving rates and the resulting economic growth are internally calculated by the model according to certain production equations, and not directly prescribed by the programmer. Second, the model allows the analysis of further market externalities besides climate change, such as monopolistic market power or property risk. Third, it is a general equilibrium model that comprises multiple economic sectors that interact with each other. Fourth, the model reproduces the existing asymmetry between government regulation and reactions of the economic sector by explicitly representing the government as the leader of a Stackelberg game.¹¹ Finally, it is a qualitative model that is not calibrated to data from a specific country.

Starting from a given inter-temporal carbon budget there are two different policy design options to achieve an economically efficient emissions reduction. *Price instruments* (taxes) reduce demand for economic factors and thus decrease emissions. In contrast, *quantity instruments* (ETS) limit emissions directly by restricting the available amount of permits and thus cumulative emissions. After first analyzing a deterministic setting in which all parameters are fixed and known by all actors, we will discuss what happens when uncertainty comes into play, for example about resource extraction costs or the learning potential of renewable energy.

For the sake of simplicity, we do not distinguish between various types of fossil resources. Therefore, emissions are proportional to resource consumption, and the problem of climate protection is reduced to the problem of fossil resource conservation.

⁹ ‘First best’ meaning the optimal solution in a world in which all markets function properly.

¹⁰ For a detailed description of the model, see Edenhofer et al. (2009 a).

¹¹ A Stackelberg game assumes a hierarchical asymmetry: one player (Stackelberg leader) makes his decision before the other players (Stackelberg followers) by considering information about the expected reaction of the followers to his move. Here, the government (leader) assumes profit-maximizing behaviour of the economic sectors (followers), who react to the tax path announced by the government.

Observations in a deterministic setting

The results of our model may at first seem surprising, but they are in fact in line with economic intuition; both types of market instruments – optimally implemented price and quantity instruments – can have the same economic efficiency. If the government possesses all necessary information for estimating economic development and no further market failures occur, an optimal emission tax as well as a cumulative permit trading scheme both achieve climate protection at minimal cost. Both instruments result in the same carbon price, which increases until backstop technologies¹² are competitive and replace their carbon-based alternatives (see Fig. 1). As expected, the price grows with the net interest rate corrected by an extraction cost term (Hotelling, 1931).

Different institutional requirements arise from choosing either a tax or an ETS. The tax requires that the government is able to impose the optimal time path of the tax (see Fig. 1), which is often hampered by political conflicts. Otherwise the private sector cannot reach its inter-temporal market equilibrium. In the case of tradable emission permits, the government has to be able to enforce the cap. Furthermore, to reach the optimal price path for the permits, the futures markets for the fixed stock of permits must be complete; it must be possible to trade permits for each time step in the future.

Distribution of rents

The carbon budget creates a scarcity rent for the permit owners. Scarcity rents are profits to the owner of a scarce good that arise from the fact that the price of the good increases when supply of the good decreases. In this case, the government decreases supply by limiting the total amount of emissions.

In this perspective, creating rents is at the heart of environmental policy. The translation of resource scarcity into rents is the reason why purely economic agents care about the environment. It is a common understanding within welfare economics that rents can be removed from private agents without distorting the efficiency of resource allocation. One advantage of an emission tax is that it transfers the rent to the government. These revenues can then be redistributed or used to reduce existing tax distortions.

In contrast, if permits are freely allocated according to previous emissions, the ETS leaves this rent to permit owners, thereby decreasing social welfare. This effect was observed during the first period of the European ETS when power companies

¹² Backstop technologies are energy technologies that do not produce any carbon dioxide and are assumed to have infinite potential. In our simplified model, renewable energies are modelled as a backstop technology.

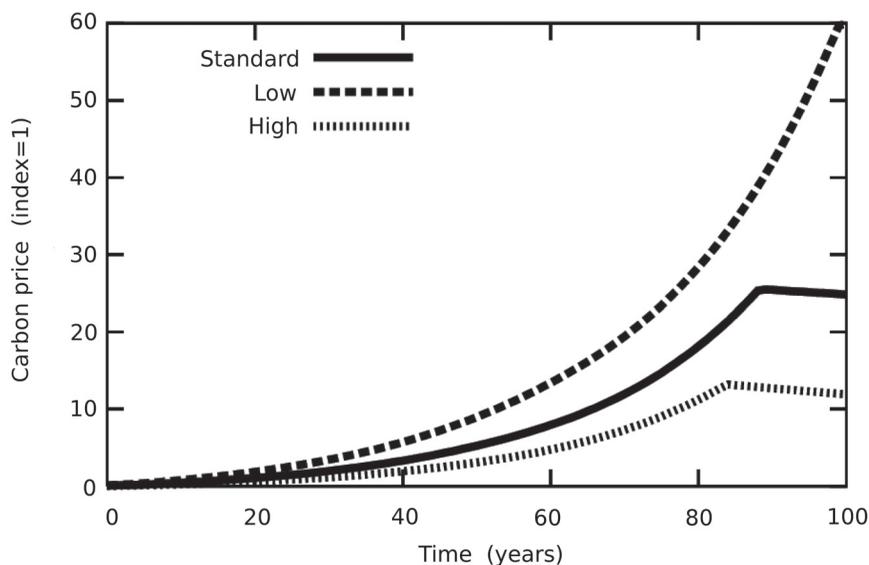


Fig. 1. Optimal carbon price in order to achieve the carbon budget (values are indexed with regard to the first year of simulation). The curve shows a kink once the backstop technology has replaced its carbon-based alternatives. Dotted lines show the sensitivity of the optimal resource tax with respect to different parameterizations of economic factors; here the cost-decreasing learning effects within renewable energy production, which are assumed to be low, high or standard. (Source: based on calculations in Edenhofer *et al.*, 2009 a)

made billions in windfall profits¹³ by incorporating market prices for emission permits into their electricity prices without actually having to pay for these permits (Sijm *et al.*, 2006). However, if the permits are fully auctioned, the rent is again transferred to the government, so the outcome is totally symmetric to using a resource tax.

Input and output regulation

Taxation or quantity regulation can be imposed on goods with different levels of refinement along the production process (for example, on the amount of fossil fuel resources, of secondary energy or of final output). To achieve efficient emission reductions, an instrument must be directly related to the economic factor causing the emission. An energy tax (output instrument) that does not discriminate between different sources of the taxed energy is generally not efficient. Although an energy

¹³ Windfall profits are unexpected profits through unforeseen changes in the market; e.g., through changed government regulation.

tax reduces emissions due to a decrease in energy consumption, it has almost no influence on factor allocation or resource substitution within the energy production process. In contrast, a resource tax (input instrument) leads to optimal factor reallocation as energy is partly replaced by capital or labour.¹⁴

Thus, internalizing an externality is most efficient when the polluting factor with most substitution possibilities is regulated, rather than some aggregated good for which no environmentally friendly substitute exists. If only the aggregated final product is regulated, (for example, by a value-added tax), consumers have no substitution possibilities; they can only reduce their demand. If energy in general is taxed, production firms can decrease secondary energy use by either decreasing output or switching to less energy-intensive production processes, so they have at least some substitution possibilities. If GHG emissions are directly taxed, many more substitution possibilities are tapped; power producers can increase power plant efficiency or use less emission-intensive options like natural gas or renewable energy, and production firms can decide to use less energy-intensive production processes or buy energy from power producers using renewable sources.

Sectoral coverage

It is worth mentioning that a regulatory instrument has to cover all relevant sectors; i.e., all resource flows through the economy (Hargrave, 2000). This can be done by an upstream system where the resource extracting sector is regulated, or by a downstream system where the producer of the final product has to report the total carbon content along the production chain of a product, and either pay taxes or buy permits for this amount of carbon (see Fig. 2). In an idealized world of complete sectoral coverage and zero monitoring and transaction costs these approaches are equivalent. If transaction costs exist, it seems plausible that regulating few actors (resource mining companies) through upstream regulation will prove easier than regulating many actors (production companies or even households) through downstream regulation. In real life, transaction costs are widely persistent and substantial, which is reflected in the difficulties of the different carbon footprint projects that try to determine how much carbon was emitted all along the production chain to produce a final good.

In real-world policy implementations, it is commonly observed that individual sectors are exempt from tax or quantity regulations (Rupp and Bailey, 2003; Bach, 2005). This decreases the coverage of production sectors by the regulation, thereby reducing substitution possibilities and strongly increasing total cost. Hence,

¹⁴ Investing in energy efficiency would be an example of replacing energy with capital, while the replacement of automated production by manual labour would represent a shift towards labour.

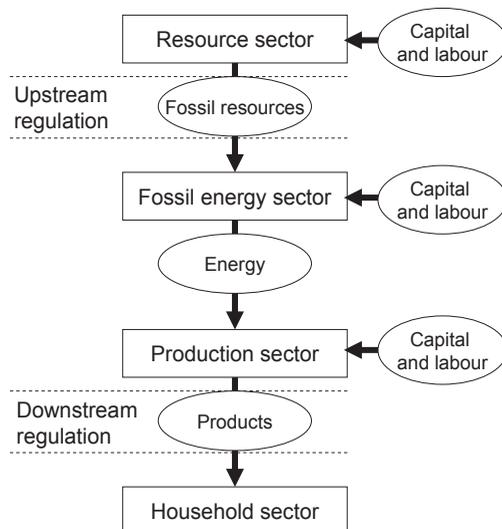


Fig. 2. Exemplary production chain. (Source: adapted from Edenhofer *et al.*, 2009 a)

exempting sectors from the regulation will lead to much higher costs for society compared to a regulation covering all sectors.

Supply-side dynamics and the green paradox

In his 2008 paper on global warming, Hans-Werner Sinn develops the ‘green paradox’. With regard to the strategic behaviour of resource owners he concludes that rising resource taxes accelerate extraction and therefore worsen global warming. His analysis relies fundamentally on the assumption that resource owners take only the resource budget given by nature into account. Thus, resource owners will extract the entire resource stock, and resource taxes will only change the timing but not the total amount of extraction. Within Sinn’s framework, an asymmetry of price and quantity instruments arises, since an ETS in which the number of permits is lower than the potential resources that could be extracted automatically restricts the total amount of resources that will be extracted. In contrast, only a few price instruments will be able to slow down resource extraction. Possible market-based policy instruments (in contrast to command-and-control instruments, such as a moratorium on coal power plants), suffer from credibility problems or high transaction costs, or imply huge, politically unfeasible transfer payments to resource owners (Edenhofer and Kalkuhl, 2009).

In our model, however, both the resource tax and the ETS will impose the carbon

budget onto the resource owners' extraction problem.¹⁵ Our resource tax is high enough and rises in such a way that it removes the rent from resource owners. As the demand-price relation for the resource is known by the regulator, the tax is fixed to the right level so that the pure extraction costs plus the tax yield a resource price at which demand is reduced to the amount allowed by the carbon budget. Thus, resource owners cannot sell more resources than the carbon budget allows without incurring losses. Another important difference between our model and Sinn's is that the mitigation target is not derived endogenously from cost-benefit analysis, but externally as a resource budget. Thus the concept of 'internalization' gains a new meaning: price as well as quantity instruments transform the resource scarcity rent into a climate rent that protects the atmosphere as a global common.

It follows from our analysis that a successful climate protection policy instrument manages to (i) devalue the resource owners' scarcity rent, and (ii) establish an optimal resource price by a public authority that governs the global common on behalf of humankind. The quantity instrument directly transforms the resource rent into a climate rent by announcing a fixed permit budget. Thus, resource owners realize that the scarce permit stock has already devalued their – now abundant – resource stock and that there is almost no room left for rent-making.

An optimal price instrument also implicitly fixes a carbon budget. However, it does not directly communicate the politically-set carbon budget; resource owners only perceive the tax rate and might ignore the fact that the government imposes the tax in such a way that it fixes the carbon budget. Thus the tax obscures the devaluation of the resource rent. If resource owners do not perceive the intended quantity effect of the tax, they cannot determine the resource extraction path correctly. The resulting extraction path then is non-optimal, which could possibly result in too much resources being extracted.

The ETS and the tax are thus only equivalent if the resource owners anticipate the correct time path of the tax and believe that the public authority is committed to safeguarding the carbon budget.

Introducing uncertainty

In real life, we do not know too much about the future – the development of oil prices or the future enforcement of energy efficiency standards are examples where our knowledge is limited and uncertainty comes into play. We therefore analyzed exemplarily the effect of wrong estimation of important parameters on our model results. To demonstrate the sensitivity of results to model parameters, Figure 1 shows

¹⁵ A more formal discussion about the explicit assumptions and technical implementations of specific policy instruments can be found in Edenhofer and Kalkuhl, (2009).

the changes in the optimal carbon price path when the cost-decreasing learning effect within renewable energy production is varied.

Optimal resource taxing

If the regulator implements a price instrument, the calculation of the optimal resource tax requires exact estimation of supply, demand, technology and substitution options – at least for the next century. These informational requirements are highly demanding and probably beyond the computational capacity of a real-world government or research institution. If the government errs in predicting crucial parameters that are related to resource consumption, it misses either the protection target (accompanied by overconsumption) or, through too restrictive climate protection, the optimal consumption path (see Fig. 3).

Optimal issuing of permits

In contrast to direct resource pricing, a quantity restriction directly controls the amount of emissions, and hence prevents violation of the climate target. However, the regulator has to decide about the timing of permit issuing, and thus faces the same uncertainties about future demand as in the tax model. Wrong estimation of economic parameters leads to suboptimal timing and causes welfare losses.

If the regulator allows banking and borrowing of permits, he shifts the uncertainties about future demand to the private sector; private agents risk their profits if they cannot predict these parameters correctly (Krysiak, 2008). Permits can be used at any time in the future. It is up to the private firms to decide *when* to use their permits according to their estimation about future permit prices.

Futures markets and institutional equivalents

For a permit market to function successfully, it is necessary that future prices are already known or that traders believe that they can predict them (Dasgupta and Heal, 1979, p. 108). Futures markets can be distorted by insecure property rights, imperfect information, limited access to markets in the future, or uncertainty about regulator's future policies. For example, the collapse of permit prices within the first trading period of the EU ETS was caused by an over-allocation of permits and the absence of banking, which would have allowed the transfer of permits to the future (see also Brunner *et al.*, 2009).

As a successful ETS will cover all relevant economic sectors and activities, the permit market will be highly fragmented and private agents will have difficulty coordinating their plans. Furthermore, assessment of futures markets requires

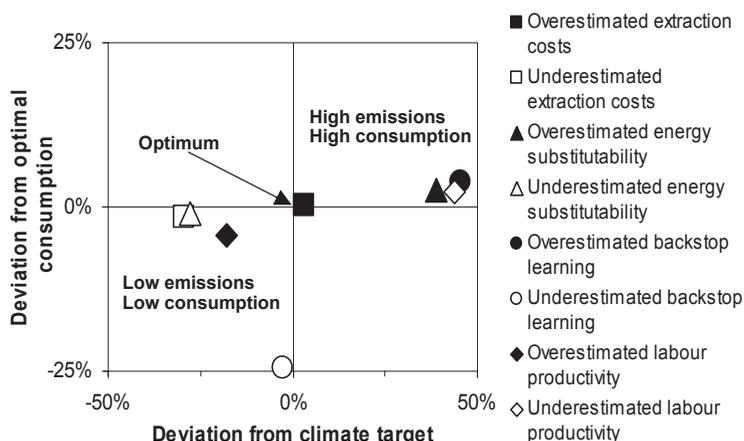


Fig. 3. Deviation from climate target and optimal consumption if the government does not estimate economic parameters correctly in order to calculate the optimal resource tax. Wrong estimation of parameters risks violating both the climate protection target as well as the cost-effective consumption target. (Source: Edenhofer *et al.*, 2009 a)

research that is always costly to undertake. Hence, in a completely deregulated permit market, only economically powerful enterprises could afford private market research and information collection. However, markets are not efficient if not all relevant information is freely available for all market participants. Therefore, an institution is required to provide information about future carbon markets, such as the costs and risks of long-term abatement options. With the Intergovernmental Panel on Climate Change (IPCC) there already exists an institution that has a very strong reputation for compiling relevant data on technologies and their costs. The reports of the IPCC could be enhanced in such a way that its content can be better captured by investors, firms and banks for financing the long-term transition to a low-carbon economy.

One possible institution that could improve the planning security of enterprises would be a carbon bank endowed with a carbon budget. Such a bank would manage permits by maximizing net present value of its permit stock. It could define trading ratios to influence the time-path of mitigation if market discount rates differ from socially optimal discount rates.¹⁶ As an independent institution like a central bank, the carbon bank reduces regulatory uncertainty about future policies that

¹⁶ The discount rate describes how future assets (bonds, capital stocks, investments, etc.) are devalued just because their pay-off lies in the future. It equals the interest rate on capital markets and depends on the economic growth rate and normative aspects about distribution of wealth over time and the valuation of future consumption compared to current consumption. A high discount rate implies a high devaluation of future consumption; a discount rate of zero values present and future consumption equally.

might be exposed to political pressure (elections or public finance). Nevertheless, it should react with flexibility to new insights into the climate system.

A market combined with research and banking institutions might respond in a more effective way to parameter changes than a government with only limited capability for fine-tuning due to the nature of the political decision-making process. Experience shows, however, that markets are not always efficient and also often suffer from failure.

A symmetric safety valve

Another possibility for reducing short-term volatility of permit prices and thereby investor risk would be to establish a symmetric safety valve as proposed by Roberts and Spence (1976), and Burtraw *et al.* (2009). Such a safety valve would take the form of a regular ETS with two constraints:

- If the permit price drops below a certain value, say EUR 15 per ton of carbon dioxide, the issuing government buys permits until the permit price rises above the price floor.
- If the permit price rises above a certain value, say EUR 300 per ton of carbon dioxide, the government sells further permits until the price drops below this price ceiling.

The price floor would reduce the risk of investment in clean technologies as investors will always receive a minimum return for their investment. The price ceiling would weaken one of the main advantages of a cap, namely that the environmental goal is reached at all times. Yet, it could soften the economic impacts of unexpected events by loosening the cap. It could thus increase the credibility and stability of the ETS; if temporal relief systems for critical times are defined in advance, the political promise of sticking to the system even through a crisis becomes more plausible.

Such a symmetric safety valve would reduce short-term market fluctuations, but not in itself lead to optimal inter-temporal permit allocation. To reach this goal, the safety valve has to be combined with the above-mentioned measures to promote functioning futures markets.

Regulation of additional market failures

In this section we discuss other forms of market failure and the policies required to correct them. A main characteristic of taxes is their capability to directly influence price. Hence, a tax is more flexible than an ETS and can often correct additional market failures that are caused by sub-optimal pricing of a single factor. It turns

out, however, that similar welfare improvements can be achieved with an ETS if it is complemented by additional policy instruments.

Monopolistic market power

Monopolistic market power in the resource sector increases the resource price above the optimal level, thus leading to a more conservative resource extraction path (see Fig. 4). Although this might contribute to climate protection, it is not an economically efficient approach as the monopolist provides resources on a sub-optimal level in order to generate substantial rents. Furthermore, it does not guarantee compliance with the carbon budget in the long run, as the resource owners will extract their whole resource stock if it is profitable to do so.¹⁷ Hence, market power in the resource sector cannot replace climate policy. On the contrary, in the case of climate protection it enhances welfare if governments not only reduce emissions but also regulate a monopolistic resource owner.

The advantage of a resource tax lies in its ability to address two market failures at the same time: the climate protection target (which is not anticipated by resource extractors) and monopolistic market power. A quantity policy cannot directly correct the effects of monopolistic market power. However, if the permit market is competitive and the total amount of emission permits is less than the total amount of resources, competition between resource owners will be increased as they will not be able to sell all of their resources. Therefore, a reduction of monopolistic power can be expected.

Expropriation risk – when ownership of resources is insecure

If resource owners expect that their property rights are insecure,¹⁸ they will change their extraction timing. As considered by Sinn (2008), risk of expropriation results in resource owners discounting their revenues at a higher rate (they add a risk premium onto the discount rate), leading to accelerated extraction (see Fig. 4). This behaviour is plausible. For example, if I am not sure that I will still be the owner of a certain oil field in 20 years, I will prefer to extract and sell the oil now at a slightly cheaper price and invest the money elsewhere rather than risk losing the oil. One option to remove the effect of expropriation risk and flatten the extraction path is to subsidize the resource price after an initial period of taxation. This makes

¹⁷ The complete extraction of the resource stock in the absence of climate policy depends on some basic assumptions about the substitutability of fossil resources and the dynamics of extraction costs, as well as on the time-frame considered.

¹⁸ One example of insecure property rights might be authoritarian regimes of oil-exporting countries that are under a certain threat of losing control over their oil resources.

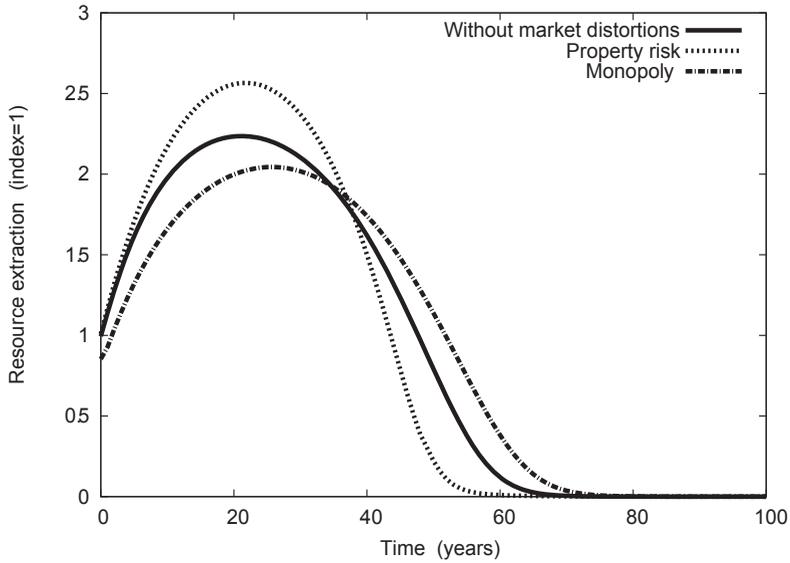


Fig. 4. Impact of several market imperfections on resource extraction. If property rights for resources are insecure, resource owners will extract the resources faster than the economic optimum, while a monopolistic resource owner will slow down resource extraction (values are indexed with regard to the first year of simulation). (Source: based on calculations in Edenhofer *et al.*, 2009 a)

future extraction more attractive than immediate extraction. However, such a subsidy shifts income from households to resource owners.

Another option is to institute an optimal price or quantity instrument that effectively expropriates the resource owners, thereby removing both the resource rent and the uncertainty of resource property rights. The problem of insecure property rights then only persists for permit owners who face regulatory uncertainties about future trading ratios or permit caps. Although the carbon budget is always adhered to, the timing in this case is suboptimal because higher effective discount rates are used to compensate for uncertainty.

Policies to push technological change

Is carbon pricing the only important action that a government should take in order to avoid dangerous climate change? Conventional economic wisdom would say yes, as *The Economist* (2008) did when it criticized subsidies for clean technologies. Admittedly, a high carbon price is an incentive for investing in clean technologies. However, carbon prices alone fail to push clean technologies towards an optimal level because usually there are additional market failures with respect to innovation-driven technologies (Edenhofer *et al.*, 2006).

Typical market failures result from the nature of knowledge; while research has to be funded by someone, the gains from the resulting knowledge will not be fully captured by the funding firm. Intellectual property rights such as patents exist, but beyond direct marketing, knowledge is spread through formal and informal channels, and advancements in production processes are copied by other firms. Therefore, society as a whole benefits from research much more than the company funding the research and development (R&D). As a consequence, individual companies will invest less than the economic optimum in R&D (Jones and Williams, 2000). Also, other spillover effects exist, such as ‘learning by doing’; for many goods, the production cost decreases by a certain amount each time that total cumulated production capacity of this good is doubled. Accordingly, all companies of a certain industry can profit from the total experience gained in that industry. This effect is readily observable for photovoltaic modules, where the cost per watt has fallen from about USD 50 to less than USD 3 over the last 33 years (Junginger *et al.*, 2008). To overcome these externalities and reach the economic optimum, economists recommend subsidies for investments that are related to spillover effects (Romer, 1986) or public R&D expenditures (Jones, 1995; Popp, 2004; Edenhofer *et al.*, 2005).

Our model supports the thesis that it is important to apply further instruments in addition to the tax or ETS. In particular, these comprise public R&D expenditures, both for energy efficiency and renewable energy technology, and investment subsidies to internalize spillovers of ‘learning by doing’ effects within the renewable energy sector. Although underinvestment in clean technology markets can be addressed by specific technology subsidies, one might ask if an additional increase of the carbon tax could induce sufficient higher investment. However, we calculated that without explicit technology subsidies, the effect of a further increase of the resource tax is not significantly different from the effect of basic quantity regulation (see Fig. 5 a). As renewable energy production remains far below its optimal level, long-term consumption is reduced remarkably in comparison to a world in which an explicit technology subsidy is implemented (see Fig. 5 b).

Summary and conclusions

It is widely accepted that a price on carbon dioxide is required for successful climate protection. This can be achieved either through price mechanisms such as taxes on emissions or through quantity mechanisms such as emissions trading schemes. In this text we discussed and compared the effects of and the issues surrounding the implementation of different price and quantity regulations under a carbon budget constraint. The following conclusions apply to the design of all instruments:

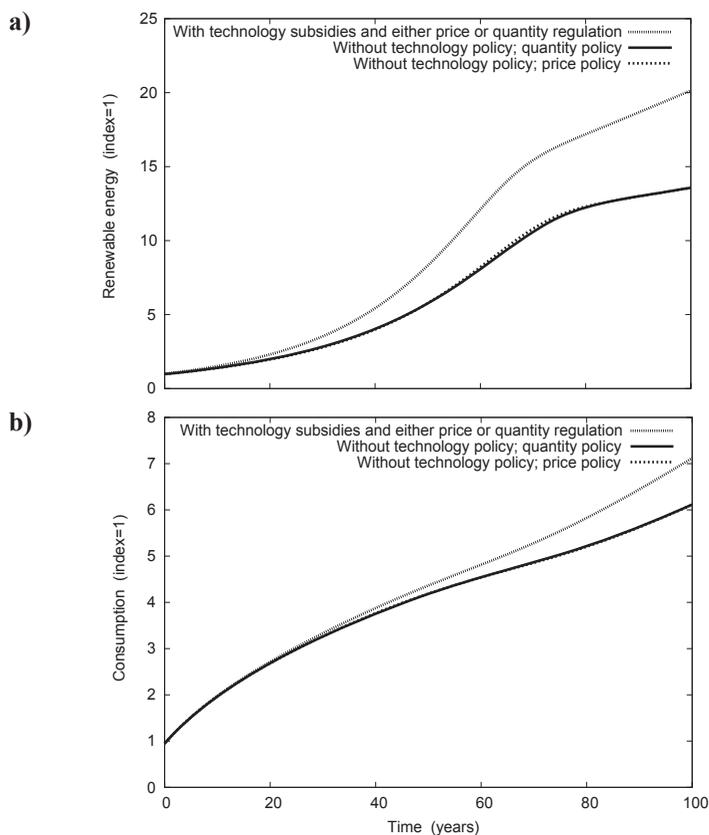


Fig. 5. a) Renewable energy production and b) total consumption of goods with and without technology policy; i.e., explicit technology subsidies (values are indexed with regard to the first year of simulation). (*Source:* based on calculations in Edenhofer *et al.*, 2009 a)

- It is important to **stabilize investor expectations** about the stringency of future carbon constraints by providing a credible long-term signal of future carbon prices. Future **carbon prices** need to be (i) **sufficiently high** and (ii) **consistent**, so that long-term investments are adjusted accordingly. This is the prerequisite for making the energy, production and transport infrastructure less carbon-intensive.
- For a price instrument, this requires a credible long-term commitment to a **rising carbon tax trajectory**. For a quantity instrument, the requirements are a **fixed total cap** and either **well-functioning futures markets** or an **institution** that **allocates** the total permits in all future times.
- Governments should capture the **scarcity rent of carbon**. Revenues from taxes or permit auctioning should be used to (i) offset distortionary taxes, (ii) subsidize abatement technologies to offset other market externalities from technological

spillover, or (iii) counteract the regressive effect of the carbon constraint (distributional equity). While carbon taxes will directly deliver annual revenues to governments, a cap-and-trade system will require auctioning of permits to raise a comparable revenue stream. Therefore, **auctioning is strongly preferred** to handing out permits for free.

- Regulation of fossil fuel **input** (e.g., a resource tax) is better than **output regulation** of secondary energy (e.g., an electricity tax) because the regulation directly addresses the pollution externality, exploiting all substitution and efficiency options along the production chain.
- The point of **regulation** should be **upstream** (at the level of fossil fuel producers and importers) rather than **downstream**, to allow broad coverage of sectors with low transaction costs.
- It is important to take into account **additional market externalities** besides climate change that affect the efficiency of taxes and quantity instruments. This includes, among other factors, the risk of **expropriation** and **monopolistic** energy markets.
- Technology spillover effects require additional policy instruments such as **subsidies for clean technologies**.
- The climate protection target will only be achieved if the **scarcity rent of resource owners is devaluated**. A cap on cumulative emissions directly communicates this devaluation, while a tax only achieves the devaluation if the regulator convinces resource owners that he will adjust the tax in such a way that he safeguards the total carbon budget. Otherwise, the resource owners might not extract resources along the optimal path, which could possibly result in excessive extraction of resources.
- If a **carbon bank** is entitled to issue allowances according to a publicly known cumulative carbon budget, the budget is made explicit and transparent, and can be anticipated easily by resource owners. If this is the case, the resource owners cannot increase their rents by deviating from the social optimal extraction path. It should be noted that even if the long-term credibility of a carbon bank can be taken for granted, the short-term volatility of prices remains a daunting issue. Thus, the main challenges for an ETS are reducing the **volatility of spot permit prices** and creating **stable expectations about future permit prices**.

The preference for a tax or a quantity instrument in a **realistic setting with uncertainty** hinges on the assessment of whether governments or markets are better suited to bear risks and make predictions about the future:

- A **price instrument** places the risk of misjudging the right tax rate on the **government**. Possible consequences of predicting the wrong mitigation costs are either

economic losses (if taxes are too high), or environmental losses due to non-compliance with the carbon budget (if taxes are too low).

- In contrast, a **quantity instrument** always achieves the environmental goal by observing the carbon budget. It moves the risk to the **economic agents**, with profit losses as a consequence of wrong predictions of future permit prices.

Although markets are often seen as more capable of collecting information than a centralized authority, this will entirely depend on the implementation of an efficient carbon market, including mature futures markets or other institutions for stabilizing future price expectations, such as insurance schemes, hedging strategies, or an international carbon bank. The choice of a quantity instrument can also provoke new market failures, as a new permit market is created that may be subject to speculations and myopic investment decisions.

Finally, since climate change is a global problem, the effort to reduce greenhouse gas emissions must be global. The long-term goal therefore should be the international harmonization of carbon prices. This will probably be more difficult to achieve with a system of national carbon taxes than with a global system or regionally inter-linked systems of emissions trading.

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