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Discussion Papers

Deutsches Institut für Wirtschaftsforschung

2013

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IMPRESSUM

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http://www.diw.de

ISSN print edition 1433-0210
ISSN electronic edition 1619-4535

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The Role of Hedging in Carbon Markets

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Abstract
In the European Emissions Trading System, power generators hold CO_2 allowances to hedge for future power sales. First, we model their aggregate hedging demand in response to changes in expectations of future fuel, carbon and power prices from forward prices. This partial equilibrium analysis is then integrated into a two period model of the supply and demand of CO_2 allowances considering also emissions impact and banking of allowances by speculative investors. We find that hedging flexibility can balance a CO_2 allowance surplus in the range of 1.1 to 1.6 billion t CO_2 at discount rates of future CO_2 allowances between 0 to 10%. If the surplus exceeds this level, then the rate at which today's carbon prices discount expected future prices increases. This points to the value of reducing the surplus, estimated to be 2.6 billion t CO_2 allowances in 2015, by about 1.3 billion t CO_2, thus ensuring that hedging makes a significant contribution to stabilise carbon prices.

Keywords: Emissions trading schemes, Banking, Power hedging, Discount rates

JEL Classifications: D84; G18; Q48

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1. Introduction

In the European Emissions Trading System (EU ETS), the cap of CO_2 allowances is fixed several years in advance and, thus, does not respond to variations in demand. In 2007, at the end of the first trading phase of the EU ETS, spot prices dropped close to zero, because the supply of expiring CO_2 allowances exceeded demand (J. Chevallier, 2011, H. Fell et al., 2011). In principle this should not happen again, because in the second trading phase, between 2008 and 2012, and in the third trading phase, between 2013 and 2020, surplus allowances can be banked for future usage. Banking constitutes additional demand for CO_2 allowances beyond firms' need to cover the emissions by the end of the current year. Firms have an incentive to bank, i.e. to hold CO_2 allowances from one year to the next if they expect future carbon prices to increase with the rate of interest (M.B. Cronshaw and J.B. Kruse, 1996). Therefore, banking allows that expectations on future market scarcity are priced into current carbon prices. As a result of banking, the carbon price in the EU ETS did not drop to zero during the second trading phase, despite an estimated surplus of 2.6 billion t CO_2 allowances in 2015 (black line in Figure 1) (K. Neuhoff et al., 2012).

Demand for the surplus of CO_2 allowances derives from hedgers and speculators[2]. To analyse the role of hedging in the EU ETS, we model hedging with CO_2 allowances by power firms and the interaction with CO_2 banking by speculative investors and CO_2 price dependent emission levels.

In the EU ETS, hedging with CO_2 allowances by power firms are the principle driver for scarcity and, thus, prices of CO_2 allowances. Power firms hold CO_2 allowances beyond their need to cover their annual emissions, as they use these allowances to hedge the carbon prices for producing power they sell several years forward. CO_2 hedging demand has gradually increased since 2008 because since 2013 power firms in Western Europe no longer receive free CO_2 allowances. The aggregate hedging demand can vary from one year to the other because power firms have flexibility in adjusting the power forward sales, and thus also fuels and CO_2. In theory, power firms can either give priority to all fossil generation capacity to hedge power sales acquiring the corresponding volume of CO_2 allowances, or they can give priority to all renewable generation capacity in order to hedge power sales and acquire less CO_2 allowances. The light grey hedging corridor in Figure 1 depicts this flexibility resulting from the power generation mix.

However, interviews suggest that power firms follow risk management procedures and, thus, have less flexibility in adjusting their CO_2 hedging volume than depicted by the light grey hedging corridor. We model the two factors determining hedging with CO_2 allowances by power firms, as identified in 13 semi-structured interviews. With deviations of forward prices from expectations by firms, the volume of power sold forward and the allocation to different generation assets is adjusted. The more expectations exceed CO_2 forward contract prices three years ahead of production, the more firms deviate from their hedging schedule contracting bigger volumes of coal, gas and CO_2 allowances three years ahead and less later on. This can result in adjustments to the CO_2 hedging demand between 1.1 to 1.6 billion t for discounting of future prices at 0 to 10% (dark grey hedging corridor in Figure 1).

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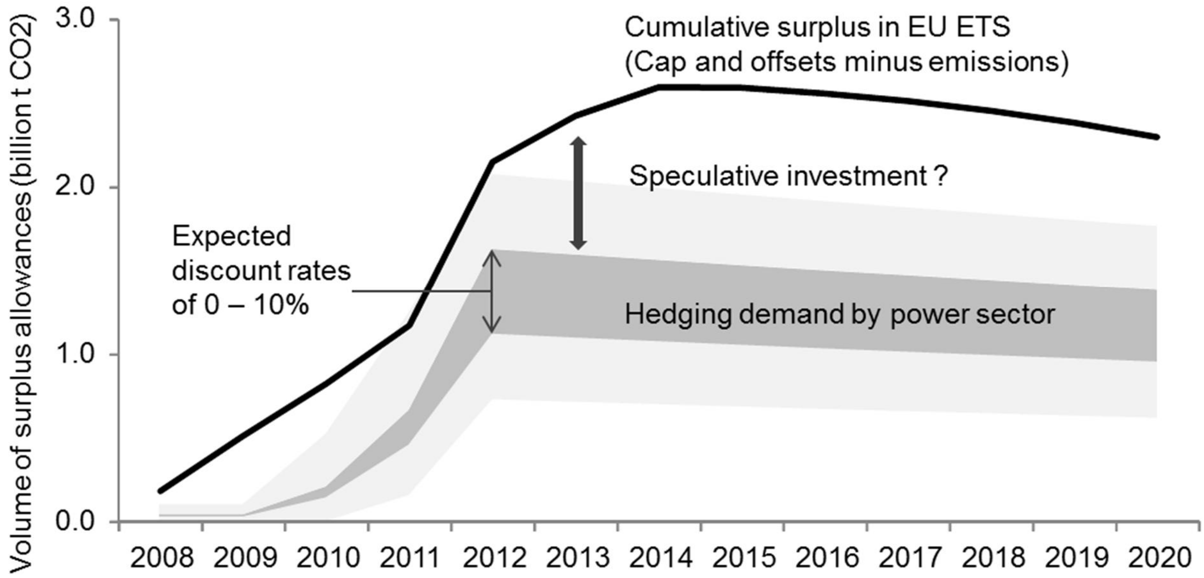
[2] Arbitrageurs also bank CO_2 allowances. Their demand does not add to the banking demand from hedgers and speculators, as their counter parties are typically hedgers, e.g. power firms.

Figure 1: Surplus of CO_2 allowances and hedging demand



Source: Own calculation based on K. Neuhoff et al. (2012)

We then model the equilibrium in the CO_2 market for a simplified two-period framework. In addition to hedging with CO_2 allowances by power firms, we consider CO_2 banking by speculative investors and CO_2 price dependent emission levels. We find that with increasing surpluses, the discrepancy between today's price and price expectations widens and the discount rates of future prices increase. Discount rates of 0 to 10% can be achieved as long as CO_2 hedging absorbs the surplus.

The paper is structured as follows: Section 2 reviews relevant literature on banking and portfolio theory. Section 3 first describes the two-period model to quantify hedging with CO_2 allowances by power firms and then presents empirical results based on the extended four-period model. Section 4 uses the resulting CO_2 hedging volume to model the market equilibrium accounting for the interaction with CO_2 banking by speculative investors and CO_2 price dependent emission levels. Section 5 draws conclusions.

2. Literature

Our analysis is built on three strands of literature. First, we challenge the literature on the intertemporal efficiency of banking and its underlying assumption of constant and low discount rates. Second, we expand the literature on modelling interactions between hedgers and speculators that bank CO_2 allowances. Third, we contribute to the literature on portfolio theory applied to hedging with CO_2 allowances by power firms.

The first strand of literature demonstrates the efficiency of banking in emissions trading, both theoretically and empirically. In theory, the intertemporal flexibility of banking can reduce overall mitigation cost, as firms are allowed to hold CO_2 allowances for future use and invest in emissions-reducing technologies, thus, distributing their emissions over time. With banking the carbon price follows the Hotelling’s rule and increases with the rate of interest (J.D. Rubin, 1996). If firms’ discount rates are higher than that of the social planner, unlimited banking and borrowing might not lead to the social optimum, as firms borrow more allowances from the future and bank less than is socially optimal. This is due to firms' discount rates determining how the carbon price increases (P. Leiby and J. Rubin, 2001).

Empirical evidence regarding the efficiency of banking of allowances does not exist yet for the EU ETS. However, it does exist for the SO_2 US Acid Rain program. A.D. Ellerman and J.P. Montero (2007) provide empirical evidence for the efficient volume of banking that allowed for reducing the overall abatement cost for the scheme. To evaluate the SO_2 allowance bank the authors assumed constant discount rates of 3 to 5%. The same discount rates are assumed in impact assessments of the EU ETS: Price projections for 2020 prices of more than 30 Euro/t CO_2 relative to prices of 20 Euro/t CO_2 in 2008 imply discount rates of 3 to 5% (Department of Energy and Climate Change, 2009, European Commission, 2008).

We challenge the assumption of unlimited banking at constant low discount rates in economic models. In line with other commodity markets, we consider that the discounting of future prices applied by buyers can depend on the strategy motivating the investment in CO_2 allowances. Hedgers hold CO_2 allowances for future use, e.g. as input in their production process and to reduce risk exposure of the firm. Speculators buy CO_2 allowances with the expectation that prices will rise more than reflected in the market. They bear the risk that their expectation is not realized and, thus, require higher rates of return than hedgers (R. E. Bailey, 2005). Therefore, we model speculators and hedgers assuming that discount rates are higher than for hedging purposes if banking of CO_2 allowances is pursued as speculative investment.

Second, P. Colla, M. Germain and V. Van Steenberghe (2012) model emissions trading between speculators and emitting firms to analyse the impact of speculators on prices and social welfare. In their model, an environmental agency allocates allowances initially to firms. Firms sell part of their free allowances to speculators in the first trading round. Once the uncertainty of demand for firms' production is resolved, they buy allowances back to cover their emissions. Speculators can charge a premium for carrying the risk from one trading period to the next. The authors find that speculators tend to reduce price volatility as speculators increase the risk-bearing capacity of the market. They also improve social welfare as long as the environmental agency is more risk tolerant than the firms.

We recognize the value of short-term intertemporal arbitrage by speculators. The question we are interested in is the role of speculators, when we have structural surplus. Our modelling framework differs, since we explicitly model CO_2 hedging through forward contracts by power firms and assume speculators either enter the market at large scale, if their required rate of return can be realised or not. In theory, speculators can buy CO_2 allowances as part of an asset portfolio including equity, bonds or alternative investments such as power generation technologies. Diversifying a portfolio might reduce risk if the assets' returns do not move into the same direction (H. Markowitz, 1952). Thus, J. Chevallier (2009) and M. Mansanet–Bataller and A. Pardo (2011) suggest that including CO_2 allowances in a portfolio of equity, bonds and energy assets can reduce risk. This derives from their finding that CO_2 allowances are not so much linked to the movement of equity and bond assets than to the power market and to the fuel switching between coal and gas as well as to the policy design of the carbon market (see also W. Blyth et al. (2009)). However, to make CO_2 allowances an attractive investment option for conservative investors, the perceived risk has to decline. The current price volatility and difficulty in modelling policy uncertainty may have increased risk perceptions. This leads us to the assumption that institutional investors will decide whether or not to include CO_2 as large scale commodity in their asset portfolio.

A third strand of literature considers the optimisation of the generation portfolio by power firms. Principally power firms treat CO_2 allowances as input cost in a power generation portfolio. To hedge exposure of their generation portfolio to price changes, power firms can sign contracts for selling power and buying the input factors such as fuels and CO_2 in advance of production at future markets. Or they can take the risk and acquire contracts on the spot market, usually one day ahead of production. P.R. Kleindorfer and L. Li (2011) aim to identify optimal generation portfolios, accounting for CO_2 as part of the generation cost. The portfolios consist of physical generation assets and financial derivatives such as forwards or options to buy. The power firms choose the mix of financial instruments in their generation portfolio in order to maximise the expected profit from sales and purchases of energy assets. This decision is constrained by the risk measure Value at Risk. In addition to identifying the optimal portfolio of financial instruments, power firms can decide on the timing of the acquisition of CO_2 allowances. In their framework the volume of CO_2 allowances to buy or sell each month depends on the current CO_2 price of the end of year future contract in relation to its mean. If the CO_2 price equals its mean, the power firm contracts CO_2 so as to cover each month of its emissions, accounting for the volume of allowances they have banked or were allocated in previous months. If the CO_2 price is below its mean and can be expected to increase in the following month, it is profitable to contract more CO_2 in this month and vice versa.

We also model CO_2 hedging by power firms considering deviations between forward contracts and firm's expectation as one important factor. This assumes that forward markets do not fully reflect all information. Instead of using a Value at Risk constraint as risk measure, we assume that power firms aiming at stable returns from power sales, manage price risks by hedging across the portfolio of generation technologies. Thus, we capture constraints on hedging positions implemented as part of corporate risk management strategies.

We do not account for firms with market power that have an incentive to hold CO_2 allowances in order to increase CO_2 prices. A.S. Malik (2002) and M. Tanaka and M.T. Chen (2012) show this for Cournot players. In M. Tanaka and M.T. Chen (2012)'s two-period model firms sell power ahead of production through forward contracts. In period two they produce power that they sold in period one or buy power at the spot market and trade CO_2 allowances. They find that firms with higher emissions rates have a stronger incentive to hold CO_2 forward contracts beyond their compliance needs in order to increase power prices. However, this does not account for the fact that power generators generally acquire, in parallel, forward contracts for the inputs required to product the power, i.e. fuels and CO_2.

Data on the actual volume of CO_2 allowances that firms hold as financial contracts for hedging or speculative purposes is not available. Data on the volume of allowances that are allocated to firms participating in the EU ETS as well as the volume of allowances that is used to cover emissions is available with a one year time lag (CITL, 2011). Few papers estimate the hedging demand for CO_2 allowances in the EU ETS. According to Eurelectric (2009, 2010) power firms sell about 10 to 20% of their power three years ahead, 30 to 50% two years ahead and 60 to 80% one year ahead of production. They argue that the power sector requires 1.3 billion CO_2 allowances by the end of 2012 in order to hedge power sales through 2015. Point Carbon (2011) derives lower estimates as they do not account for the use of international offsets that can also be used as part of the hedging portfolio. According to their calculations, the power sector needs 650 million CO_2 allowances by the end of 2012 and 950 million CO_2 allowances by 2013.

Thus, our paper expands the previous literature by accounting for both the strategy of power firms to hedge across the portfolio and the flexibility of power firms in adjusting the hedging demand for CO_2 allowances to their expectations of future prices as well as the interaction with CO_2 banking by speculative investors at higher discount rates.

3. Hedging with CO_2 allowances by power firms

3.1. Two-period model of CO_2 hedging by power firms

We formulate a partial equilibrium model in order to analyse the factors that determine the CO_2 hedging volume. The model assumes a firm producing power of E per year from coal, C, and gas, G. The coal-fired power plants produce power with a thermal efficiency of f^c and the gas plants with a thermal efficiency of f^g. The CO_2 hedging volume depends on the volume of power sold forward. To reduce the exposure to price risks and profit volatility from power production, firms sell power several years ahead of production. To secure prices of the power generation inputs, firms buy coal, gas, or CO_2–free generation technologies in advance. Therefore, firms also buy CO_2 allowances in advance to cover future emissions from carbon intensive power generation technologies.

In the model the firm sells power on forward contracts in the years prior to production and, at the same time, acquires forward contracts for the fuels required for production. Within the last year the firm contracts the remaining power to match projected generation. The model focuses on the forward contracting strategy, as this has the largest impact on total hedging demand, and does not capture adjustments to contracts in the final year. First, we illustrate the approach using a two-period model, and subsequently present results calibrated to the empirical observed contracting strategy, therefore allowing for up to four years of forward contracting.

Interviews with 13 power firms[3] suggest that the volume and the period for which power is sold forward is a corporate strategy decision. Based on its expected generation portfolio, the firm

[3] Following purposive sampling we contacted the main power firms in Western Europe, since they do not receive free CO_2 allowances from 2013 onwards (McCracken, G. 1988. *The Long Interview*. Thousand Oaks: Sage.). Hedging experts from 13 power firms responded: Badenova, Dong, EDF, Enel, EnBW, GDF Suez, Iberdrola, MVV Energie, Enercity, Stadtwerke München, RWE, Statkraft, Vattenfall. We conducted semi-structured interviews in 2012 (Manheim, J.; R. Rich; L. Willnat and C. Brians. 2012. *Empirical Political Analysis*. London: Pearson.). The interviews focused on three main questions: what are the main factors that determine hedging with CO_2 allowances, how the hedging strategy is formulated, and when it is worth to deviate from the hedging strategy. The 13 interviewed power firms account for 65% of Western European power production and 56% of European power production (Badenova. 2011. "Geschäftsbericht 2010," Freiburg: Badenova, p.32, DONG Energy. 2011. "Annual Report 2010.," Fredericia: DONG Energy, p.3., EDF. 2011. "Activity and Sustainable Development 2010," Paris: EDF Group, p.3-5., Enel. 2011. "Annual Report 2010," Rome: Enel, p.22., EnBW. 2011. "Annual Report 2010," Karlsruhe: EnBW Energie Baden-Württemberg, p.1., GDF Suez. 2011. "Reference Document 2010," Courbevoie: GDF Suez, p.10-11., Iberdrola. 2011. "Annual Report 2010," Bilbao: Iberdrola Group, p.8., MVV Energie. 2010. "Geschäftsbericht 2010/11," Mannheim: MVV Energie, p.62., Enercity. 2011. "Energiemomente Report 2010," Hannover: Enercity Stadtwerke Hannover, p.34., Stadtwerke München. 2011. "Jahresbericht 2010," München: Stadtwerke München (SWM), p.60., RWE. 2011. "Annual

formulates a hedging schedule: γ_1% of power are sold in year one and γ_2% are sold in year two. In the interviews, it was also reported that open positions in power sales are avoided. This implies that the power forward sale in year one must be matched by forward contracts for the inputs required to produce the power $e_1 = c_1 + g_1$. Several power firms reported that they prefer to hedge across the portfolio of their generation assets rather than hedging with a strong emphasis on one specific generation technology. Accordingly, the firm buys γ_1% of coal and gas in year one and γ_2% in year two. However, firms can deviate from this proportional hedging schedule. To reflect both the preference to hedge across the portfolio and the opportunities for adjustment, deviations from the formulated hedging schedule are captured as quadratic penalty:

$$-\alpha((\gamma_1 * C - c_1)^2 + (\gamma_1 * G - g_1)^2). \quad (1)$$

When firms' expectations about future energy and carbon prices differ from forward contract prices in the market, it impacts the CO_2 hedging volume. For example, if carbon prices are currently low, but are expected to increase, this creates an incentive for power firms to prioritise hedging future power sales with generation by carbon intensive assets, as this allows for early contracting of carbon at lower prices. As a result, the hedging demand for CO_2 increases. The interviews suggest that this prioritisation of generation technologies is based on expected profits. Of the power that the firm will produce in year two it sells e_1 in year one and $E - e_1$ in year two. In year one the firm thus expects revenues that depend on the forward prices in year one p_1^e and the expected price in year two $E(p_2^e)$:

$$e_1 * p_1^e + (E - e_1)\, E(p_2^e). \quad (2)$$

The firm also signs forward contracts in year one for the coal and gas inputs to produce power, and acquires the remaining fuel volumes in year two:

$$c_1 * \frac{p_1^c}{f^c} + (C - c_1)\frac{E(p_2^c)}{f^c} + g_1 * \frac{p_1^g}{f^g} + (G - g_1) * \frac{E(p_2^g)}{f^g}, \quad (3)$$

The firm does not hedge more than it can generate ($C \geq c_1$; $G \geq g_1$). In addition, the firm needs to buy carbon to hedge the power production from coal and gas. The required volume of CO_2 allowances to cover the emissions depends on the carbon intensity of the coal plants i_{CO2}^g and of the gas plants i_{CO2}^g. The firm considers forward contract prices for CO_2 allowances in year one p_1^{CO2} and its expectations of carbon prices for year two $E(p_2^{CO2})$. The expected carbon costs are:

$$c_1 * i_{CO2}^c * p_1^{CO2} + (C - c_1)\, i_{CO2}^c * E(p_2^{CO2}) + g_1 * i_{CO2}^g * p_1^{CO2} + (G - g_1)\, i_{CO2}^g * E(p_2^{CO2}). \quad (4)$$

Thus, the power firm chooses the contract volume of coal and gas in year one, so as to maximise the expected profit (combining equations (1) to (4) and substituting e_1 by $c_1 + g_1$):

$$\max_{c_1, g_1} E(\pi) = \max_{c_1, g_1} -(c_1 + g_1)(E(p_2^e) - p_1^e) + (C + G)\, E(p_2^e) + c_1 \left(\frac{E(p_2^c) - p_1^c}{f^c} + \right. \quad (5)$$

Report 2010," Essen: RWE, p.80., Statkraft. 2011. "Annual Report 2010," Oslo: Statkraft SF, p.4., Vattenfall. 2011. "2010 Annual Report," Stockholm: Vattenfall, p.1.)

$i_{CO2}^{c}(E(p_2^{CO2}) - p_1^{CO2})\Big) - C\left(\frac{E(p_2^c)}{f^c} + i_{CO2}^{c} * E(p_2^{CO2})\right) + g_1\left(\frac{E(p_2^g)-p_1^g}{f^g} + i_{CO2}^{g}(E(p_2^{CO2}) - p_1^{CO2})\right) - G\left(\frac{E(p_2^g)}{f^g} + i_{CO2}^{g} * E(p_2^{CO2})\right) - \alpha((\gamma_1 * C - c_1)^2 + (\gamma_1 * G - g_1)^2).$

The profit function is subject to the following constraints:

$$C - c_1 \geq 0, \tag{6}$$

$$G - g_1 \geq 0, \tag{7}$$

$$c_1,\ g_1 \geq 0. \tag{8}$$

The associated Lagrangian is:

$$\max_{c_1, g_1, \lambda_1, \lambda_2} L = \max_{c_1, g_1, \lambda_1, \lambda_2} -(c_1 + g_1)(E(p_2^e) - p_1^e) + (C + G)\, E(p_2^e) + c_1\left(\frac{E(p_2^c)-p_1^c}{f^c} + i_{CO2}^{c}(E(p_2^{CO2}) - p_1^{CO2})\right) - C\left(\frac{E(p_2^c)}{f^c} + i_{CO2}^{c} * E(p_2^{CO2})\right) + g_1\left(\frac{E(p_2^g)-p_1^g}{f^g} + i_{CO2}^{g}(E(p_2^{CO2}) - p_1^{CO2})\right) - G\left(\frac{E(p_2^g)}{f^g} + i_{CO2}^{g} * E(p_2^{CO2})\right) - \alpha((\gamma_1 * C - c_1)^2 + (\gamma_1 * G - g_1)^2) + \lambda_1(C - c_1) + \lambda_2(G - g_1). \tag{9}$$

The first order (Karush–Kuhn–Tucker) conditions are the following:

$$\frac{\partial L}{\partial c_1} = -(E(p_2^e) - p_1^e) + \frac{E(p_2^c) - p_1^c}{f^c} + i_{CO2}^{c}(E(p_2^{CO2}) - p_1^{CO2}) + 2\alpha\,(\gamma_1 * C - c_1) - \lambda_1 = 0, \tag{10}$$

$$\frac{\partial L}{\partial g_1} = -(E(p_2^e) - p_1^e) + \frac{E(p_2^g) - p_1^g}{f^g} + i_{CO2}^{g}(E(p_2^{CO2}) - p_1^{CO2}) + 2\alpha\,(\gamma_1 * G - g_1) - \lambda_2 = 0, \tag{11}$$

$$\frac{\partial L}{\partial \lambda_1} = C - c_1 \geq 0, \qquad \lambda_1 \geq 0, \qquad (C - c_1)\lambda_1 = 0, \tag{12}$$

$$\frac{\partial L}{\partial \lambda_2} = G - g_1 \geq 0, \qquad \lambda_2 \geq 0, \qquad (G - g_1)\lambda_2 = 0, \tag{13}$$

$$c_1,\ g_1 \geq 0. \tag{14}$$

With $\lambda_1 = 0, \lambda_2 = 0$ and $C - c_1 \geq 0$, $G - g_1 \geq 0$ (internal solution) equations (10) and (11) can be rewritten as:

$$c_1 = \frac{1}{2\alpha}\left(-(E(p_2^e) - p_1^e) + \frac{E(p_2^c)-p_1^c}{f^c} + i_{CO2}^{c}(E(p_2^{CO2}) - p_1^{CO2})\right) + \gamma_1 * C, \tag{15}$$

$$g_1 = \frac{1}{2\alpha}\left(-(E(p_2^e) - p_1^e) + \frac{E(p_2^g)-p_1^g}{f^g} + i_{CO2}^{g}(E(p_2^{CO2}) - p_1^{CO2})\right) + \gamma_1 * G. \tag{16}$$

If expectations for power, coal and gas match forward contracts for these commodities, equations (15) and (16) reduce to:

$$c_1 = \frac{1}{2\alpha} * i_{CO2}^c (E(p_2^{CO2}) - p_1^{CO2}) + \gamma_1 * C, \quad (17)$$

$$g_1 = \frac{1}{2\alpha} * i_{CO2}^g (E(p_2^{CO2}) - p_1^{CO2}) + \gamma_1 * G. \quad (18)$$

From the optimal coal and gas volumes contracted in year one results the hedging volume of CO_2 allowances that are acquired in year one to hedge production in year two:

$$\begin{aligned} h_1 &= c_1 * i_{CO2}^c + g_1 * i_{CO2}^g \\ &= \left(\frac{1}{2\alpha} * i_{CO2}^c (E(p_2^{CO2}) - p_1^{CO2}) + \gamma_1 * C\right) i_{CO2}^c + \left(\frac{1}{2\alpha} * i_{CO2}^g (E(p_2^{CO2}) - p_1^{CO2}) + \gamma_1 * G\right) i_{CO2}^g. \end{aligned} \quad (19)$$

Equation (19) reduces to the hedging schedule $(\gamma_1 * C * i_{CO2}^c + \gamma_1 * G * i_{CO2}^g)$, if expectations of future carbon prices match forward contracts for CO_2 allowances. If expectations are higher $(E(p_2^{CO2}) = (1 + \delta_{CO2}^e)\, p_1^{CO2} > p_1^{CO2})$, it may be attractive for power firms to deviate from their hedging schedule and to contract greater volumes of coal $(c_1 > \gamma_1 * C)$ and gas $(g_1 > \gamma_1 * G)$ in year one. In this case the hedging demand for CO_2 allowances increases in year one and decreases in year two. Accordingly, if expectations are lower, the hedging demand for CO_2 allowances decreases in year one and increases in year two compared to the hedging schedule.

3.2. Parameterisation of aggregate CO_2 hedging

To quantify the aggregate CO_2 hedging demand by the power sector, we extend the model to four years $(i: 1,2,3,4)$ and to three generation technologies: coal C, gas G and non-fossils R (see Annex). Similar to the two-period model, it is attractive for power firms to deviate from their hedging schedule when their expectations of future carbon prices differ from forward contract prices. To hedge power that they will produce in year four, they can buy forward contracts for CO_2 allowances at market rate three years ahead $(p_1^{CO2}(1 + \delta_{CO2}^m)^4)$. If their expectations differ from the market rate $(\delta_{CO2}^e \neq \delta_{CO2}^m)$, they can wait one year and buy forward contracts two years ahead $(p_1^{CO2}(1 + \delta_{CO2}^m)^3\,(1 + \delta_{CO2}^e)^1)$, they can buy forward contracts one year ahead $(p_1^{CO2}(1 + \delta_{CO2}^m)^2\,(1 + \delta_{CO2}^e)^2)$, or they can buy forward contracts in the final year $(p_1^{CO2}(1 + \delta_{CO2}^m)^1\,(1 + \delta_{CO2}^e)^3)$.

To quantify bottom-up the aggregate hedging demand in the power sector, we need the average weighted hedging schedule of Western European power firms. Three power firms disclosed their hedging schedule in 2010 annual reports (E.ON, 2011, RWE, 2011, Vattenfall, 2011). Assuming the hedging schedule as suggested by Eurelectric (2010) for the remaining firms and weighting the hedging schedule with the firms' fossil fuel share, we can calculate the average weighted schedule to hedge power: 20% of power production three years ahead, 46% two years ahead, 84% one year ahead of production. Table 1 shows that the aggregate hedging demand for CO_2 allowances has increased since 2010 because many power firms acquire their CO_2 allowances in auctions and, since 2013, no longer receive them for free. This calculation excludes hedging demand from Eastern European utilities since they will continue to receive free allowances in the third trading period.

Table 1: Aggregate hedging schedule (yearly average in %)

Year j \ Year i	2010	2011	2012	2013
2013	20	46	84	0
2014	0	20	46	84
2015	0	0	20	46
2016	0	0	0	20
% of power hedged by year i for years j	20	66	150	150

To calibrate the parameter, α, that introduces the quadratic term penalizing for deviations from the hedging schedule, we use information from the interviews. In interviews it was reported that one to four Euro/t CO_2 difference between their carbon price expectation and market development are required to deviate from the hedging schedule. For example, $\alpha = 0.00000000845$ corresponds to a 10% increase in hedging demand for a one Euro increase in price expectation as compared to forward contract prices $\left(p_1^{CO2}(1 + \delta_{CO2}^{e})^4 = p_1^{CO2}(1 + \delta_{CO2}^{m})^4 + 1\ Euro\right)$. The parameter α can be interpreted as internal transaction cost. The parameters used to quantify the hedging demand in the power sector are summarized in Table 2.

Table 2: Prices and parameter assumptions (for all scenarios)

Parameter	Unit	Value	Source
α_1		0.00000000845	1 EUR, Δ10% hedging
p_1^{CO2}	EUR/ t CO_2	20	
p_1^{e}	EUR/MWh	51.40	
p_1^{c}	EUR/MWh	12.10	EEX (2012)
p_1^{g}	EUR/MWh	26.90	
C	MWh	639,103,440	
G	MWh	718,991,370	E.ON (2011), EDF(2011) EnBW (2011), Enel (2011), Eurelectric (2010), Eurostat (2012), GDF Suez (2011), Iberdrola (2011), RWE (2011), Statkraft (2011), Vattenfall (2011)
R	MWh	1,295,260,000	
γ_1	%	20	
γ_2	%	46	
γ_3	%	84	
i_{CO2}^{c}	t CO_2/MWh	0.96	IPCC (2006)
i_{CO2}^{g}	t CO_2/MWh	0.41	
f^{c}	%	40.80	IEA et al. (2010)
f^{g}	%	55.10	

3.3. Quantification of aggregate CO_2 hedging

We use three scenarios of carbon price expectations to assess their impact on the aggregate hedging demand: In Scenario 1 future prices are expected to develop at 0% instead of 5%, as suggested by CO_2 forward contract prices. In Scenario 2 future price expectations match forward contract prices (δ^m_{CO2} = δ^e_{CO2} = 5%). In Scenario 3 future price expectations exceed forward contract prices. Thus the expected rate of CO_2 price development is 10% and the market rate is 5%.

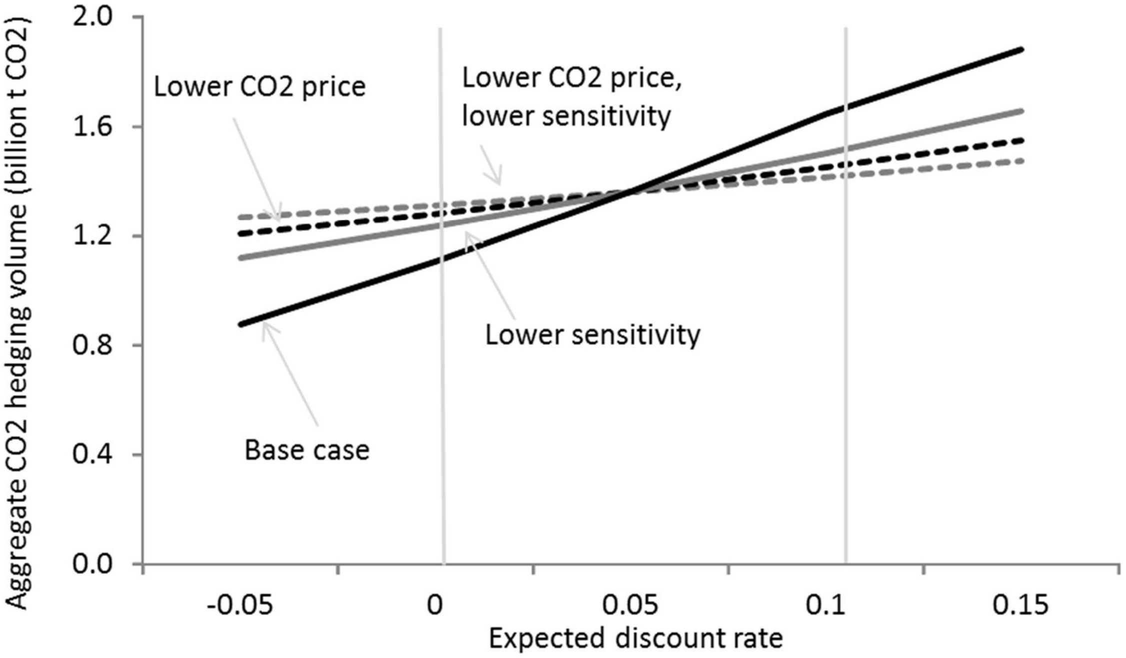
The hedging model is formulated as a mixed complementarity problem and programmed in GAMS. Table 3 summarises the contracting volumes of coal, gas and non-fossils for three price development scenarios and the corresponding CO_2 hedging volumes. Thus, the CO_2 hedging volume three years ahead of production can range from 92 to 272 million t CO_2, depending on the differences of price expectations from forward contract prices. The volume of CO_2 allowances that are acquired in the final year can range from 46 to 227 million t CO_2. The aggregate CO_2 hedging demand ranges from 1.10 to 1.65 billion t CO_2 by the end of 2012.

Table 3: Model results - Contracted volumes of coal, gas and non-fossils and CO_2 hedging

Variable	Unit	Scenario 1 δ^m_{CO2} = 5%, δ^e_{CO2} = 0%	Scenario 2 δ^m_{CO2} = δ^e_{CO2} = 5%	Scenario 3 δ^m_{CO2} = 5%, δ^e_{CO2} = 10%
c_1	MWh	62,062,110	127,820,700	193,579,300
c_2	MWh	169,298,300	166,166,900	169,298,300
c_3	MWh	245,841,600	242,859,300	246,139,800
c_4	MWh	161,901,500	102,256,600	30,086,140
g_1	MWh	78,039,690	143,798,300	209,556,900
g_2	MWh	190,069,100	186,937,800	190,069,100
g_3	MWh	276,199,000	273,216,700	276,497,200
g_4	MWh	174,683,600	115,038,600	42,868,200
r_1	MWh	259,052,000	259,052,000	259,052,000
r_2	MWh	336,767,600	336,767,600	336,767,600
r_3	MWh	492,198,800	492,198,800	492,198,800
r_4	MWh	207,241,600	207,241,600	207,241,600
h_1	t CO_2	91,575,900	181,665,200	271,754,400
h_2	t CO_2	240,454,700	236,164,700	240,454,700
h_3	t CO_2	349,249,500	345,163,800	349,658,000
h_4	t CO_2	227,045,700	145,332,100	46,458,650
H	t CO_2	1,104,886,000	1,362,489,000	1,645,831,000

Figure 2 shows the aggregate hedging demand for different expected discount rates and transaction cost parameters.

Figure 2: Flexibility in aggregate CO_2 hedging volume for different expected discount rates



Lower sensitivity: Δ2 €/tCO2 → Δ 10% CO2 hedging   Lower CO2 price: p1=7.5 €/tCO2

The results are consistent with economic intuition. If the expected price developments match carbon forward price development of 5%, the power firms follow the hedging schedule of 20% three years ahead, 46% two years ahead and 84% one year ahead of production. This corresponds to an aggregate hedging demand of 1.36 billion t CO_2 by the end of 2012. If price expectations exceed carbon forward contract prices at market rates, the CO_2 hedging demand increases beyond the hedging schedule. Similarly, if the price expectations are below carbon forward contract prices, hedging demand decreases below the hedging schedule.

To check the sensitivity of our results to the firm's internal transaction cost, the parameter that introduces the quadratic term penalising for deviations from the hedging schedule, we consider:

- A lower CO_2 price of forward contract: 7.5 Euro/t CO_2 instead of 20 Euro/t CO_2,
- Lower sensitivity: 2 Euro/t CO_2 deviations between expectations and forward contracts instead of 1 Euro/t CO_2 induce a 10% increase in hedging volume

In general, the higher firms' internal transaction cost are, the lower their flexibility to adjust their hedging demand to their price expectations. If we consider a lower carbon price of 7.5 instead of 20 Euro/t CO_2, discount rates of 0 to 10% result in adjustments to the CO_2 hedging demand between 1.3 to 1.5 billion t (black dotted line).

4. Interactions of CO_2 hedging, banking and surplus

4.1. Two-period model of CO_2 hedging, banking and surplus

To capture the interaction between the demand for CO_2 allowances from hedgers and speculators and the surplus, we expand the two-period hedging model. The surplus captures CO_2 price dependent emission levels. First, it is composed of the volume of allowances that are allocated or auctioned within the EU ETS plus the volume of imported international offsets minus emissions (θ). Second, with increasing carbon prices, emissions decrease, fewer CO_2 allowances are needed and the surplus of CO_2 allowances increases $(\beta * p^{CO2})$. The surplus $Q_1^{surplus}$ can be formulated as an upward-sloping linear curve for period one:

$$Q_1^{surplus} = \theta_1 + \beta_1 * p_1^{CO2} \tag{27}$$

and period two:

$$Q_2^{surplus} = \theta_2 + \beta_2 * p_2^{CO2}. \tag{28}$$

The unused allowances from period one can be banked for usage in period two. Demand for these allowances derives from hedgers Q^h and speculators Q^s . The hedging demand is formulated as in equation (19). To account in the two-period model for forward market prices increasing at the rate δ_{CO2}^e each year as in the four-period hedging model, we divide the expected price for period two by the parameter ω:

$$Q_1^h = \left(\frac{1}{2\alpha} * i_{CO2}^c \left(\frac{E(p_2^{CO2})}{\omega} - p_1^{CO2}\right) + \gamma * C\right) i_{CO2}^c + \left(\frac{1}{2\alpha} * i_{CO2}^g \left(\frac{E(p_2^{CO2})}{\omega} - p_1^{CO2}\right) + \gamma * G\right) i_{CO2}^g \tag{29}$$

Speculators buy CO_2 allowances as open positions and, thus, bear the risk that CO_2 prices evolve differently than expected. Speculators have an incentive to acquire CO_2 allowances $(Q^s \geq 0)$, if they expect carbon prices to increase at the discount rate exceeding their return requirements $(\delta_{CO2}^e \geq \delta_{CO2}^s)$. The discount rate refers to the growth rate between the forward contract price in period one and the expected carbon price in period two $\left(\delta_{CO2}^e = E(p_2^{CO2})/p_1^{CO2} - 1\right)$. Thus, the speculative demand can be formulated as maximum function:

$$Q_1^s = \max\left(\varphi \left(\frac{E(p_2^{CO2}) - p_1^{CO2}}{p_1^{CO2}} - \delta_{CO2}^s\right), 0\right) \tag{30}$$

The speculative demand increases with the expected carbon price in period two and decreases with the forward contract price in period one. The increase in the speculative demand depends also on the factor φ. For φ toward infinity it is assumed that a fixed large volume of speculative demand is available at return rate δ_{CO2}^s.

Equations (30) and (31) form the aggregate demand in period one. Equalising demand to the cumulative market surplus yields the equilibrium price. The market equilibrium in period one is:

$$Q_1^{surplus} - Q_1^h - Q_1^s = 0$$
$$\Leftrightarrow \theta_1 + \beta_1 * p_1^{CO2} - \left(\frac{1}{2\alpha} * i_{CO2}^c \left(\frac{E(p_2^{CO2})}{\omega} - p_1^{CO2}\right) + \gamma * C\right) i_{CO2}^c$$
$$- \left(\frac{1}{2\alpha} * i_{CO2}^g \left(\frac{E(p_2^{CO2})}{\omega} - p_1^{CO2}\right) + \gamma * G\right) i_{CO2}^g - \max\left(\varphi \left(\frac{E(p_2^{CO2}) - p_1^{CO2}}{p_1^{CO2}} - \delta_{CO2}^s\right), 0\right) = 0 \quad (31)$$

An increase in θ_1, for example, an unexpected emission shortfall, triggers a price reduction in period one. This in turn triggers a combination of emission increase in period one and an increase in banking and hedging in period two.

In period two, the surplus and the volume of allowances transferred from period one through banking and hedging needs to be in balance. In the two-period model we ignore banking and hedging demand of allowances towards later periods:

$$Q_2^{surplus} + Q_1^h + Q_1^s = 0$$
$$\Leftrightarrow \theta_2 + \beta_2 * E(p_2^{CO2}) + \left(\frac{1}{2\alpha} * i_{CO2}^c \left(\frac{E(p_2^{CO2})}{\omega} - p_1^{CO2}\right) + \gamma * C\right) i_{CO2}^c$$
$$+ \left(\frac{1}{2\alpha} * i_{CO2}^g \left(\frac{E(p_2^{CO2})}{\omega} - p_1^{CO2}\right) + \gamma * G\right) i_{CO2}^g + \max\left(\varphi \left(\frac{E(p_2^{CO2}) - p_1^{CO2}}{p_1^{CO2}} - \delta_{CO2}^s\right), 0\right) = 0 \quad (32)$$

Equilibrium in case of no speculative demand

We first assume that speculative demand is zero because $\frac{E(p_2^{CO2}) - p_1^{CO2}}{p_1^{CO2}} < \delta_{CO2}^s$. Solving the market equilibrium in equation (31) for the price in period one yields:

$$\Leftrightarrow p_1^{CO2} = -\frac{\theta_1 - \gamma\left(C * i_{CO2}^c + G * i_{CO2}^g\right) - \frac{E(p_2^{CO2})}{\omega} * \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}}{\beta_1 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}} \quad (33)$$

Similarly, solving the market equilibrium in equation (32) for the price in period two yields:

$$\Leftrightarrow E(p_2^{CO2}) = \frac{-\theta_2 - \gamma\left(C * i_{CO2}^c + G * i_{CO2}^g\right) + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha} p_1^{CO2}}{\beta_2 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha\omega}} \quad (34)$$

Plugging in the equilibrium condition for period one in the equilibrium condition for period two, the price in period two $E\left(p_2^{CO2}\right)$ is:

$$\Leftrightarrow E(p_2^{CO2}) = \frac{-\theta_2 * \beta_1 - (\theta_1 + \theta_2)\frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha} - \gamma * \beta_1\left(C * i_{CO2}^c + G * i_{CO2}^g\right)}{\left(\beta_1 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}\right)\left(\beta_2 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha\omega}\right) - \frac{1}{\omega} * \left(\frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}\right)^2} \quad (35)$$

Accordingly, this leads to an equilibrium price in period one of:

$$p_1^{CO2} = \frac{-\theta_1 + \gamma\left(C * i_{CO2}^c + G * i_{CO2}^g\right)}{\beta_1 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}} + \frac{\frac{1}{\omega} * \left(-\theta_2 * \beta_1 - (\theta_1 + \theta_2)\frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha} - \gamma * \beta_1\left(C * i_{CO2}^c + G * i_{CO2}^g\right)\right)\frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}}{\left(\left(\beta_1 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}\right)\left(\beta_2 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha\omega}\right) - \frac{1}{\omega} * \left(\frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}\right)^2\right)\left(\beta_1 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\alpha}\right)} \quad (36)$$

In equilibrium the prices decrease with increasing θ_1 and θ_2. Similarly, the prices decrease with increasing responsiveness of emissions in period one (β_1) and two (β_2). If the hedging schedule increases in period one $\left(\gamma * C * i_{CO2}^c + \gamma * G * i_{CO2}^g\right)$ and adds to the surplus in period two, the price in period two decreases. The effect is amplified with increasing emission responsiveness in period one.

Equilibrium in case of speculative demand

We now assume that the banking volume from period one and therefore the price difference between the periods increases to the level that speculative demand is attracted $\frac{E(p_2^{CO2})-p_1^{CO2}}{p_1^{CO2}} \geq \delta_{CO2}^s$. To simplify the calculations we assume $\varphi \to \infty$. If Q_1^s is not infinite, but a positive fixed number, then $\frac{E(p_2^{CO2})-p_1^{CO2}}{p_1^{CO2}} = \delta_{CO2}^s$. Combining this with the allowance balance across the periods

$$\begin{aligned} &Q_1^{surplus} - Q_1^h - Q_1^s + Q_2^{surplus} + Q_1^h + Q_1^s = 0 \\ &\Leftrightarrow \theta_1 + \beta_1 * p_1^{CO2} + \theta_2 + \beta_2 * E(p_2^{CO2}) = 0 \end{aligned} \quad (37)$$

provides the equilibrium prices $p_1^{CO2^*}$ and $E\left(p_2^{CO2}\right)^*$:

$$p_1^{CO2^*} = \frac{-(\theta_1 + \theta_2)}{\beta_1 + \beta_2(1 + \delta_{CO2}^s)} \quad (38)$$

$$E(p_2^{CO2})^* = \frac{-(\theta_1 + \theta_2)(1 + \delta_{CO2}^s)}{\beta_1 + \beta_2(1 + \delta_{CO2}^s)} \quad (39)$$

As in the case without speculative demand, the equilibrium prices decrease with increasing surplus in period one (θ_1) and two (θ_2) and increasing responsiveness of emissions in period one (β_1) and two (β_2). The higher the required rate of return (δ_{CO2}^s) is, the lower the prices in equilibrium are.

4.2. Parameterisation of CO_2 hedging, banking and surplus

To calibrate the model, we use the parameters in Table 4. We calibrate θ_1 and θ_2 to obtain banking at low discount rates, which was assumed by economists and policy makers at the beginning of the second trading period of the EU ETS (European Commission, 2008). Thus, 5% discounting of 2020 price expectations of 30 Euro/t CO_2 imply a 2012 price of 20 Euro/t CO_2. Low discounting requires θ_1 = 0.8 billion t CO_2, so that CO_2 hedging matches the surplus ($Q_1^h = Q_1^{surplus}$ = 1.4 billion t CO_2) and no speculators are needed to balance the market. To achieve overall equilibrium, the surplus post 2020 must be negative, $Q_2^{surplus}$ = -1.4 billion t CO_2, and hence θ_2 = -2 billion t CO_2.

Table 4: Parameter assumptions

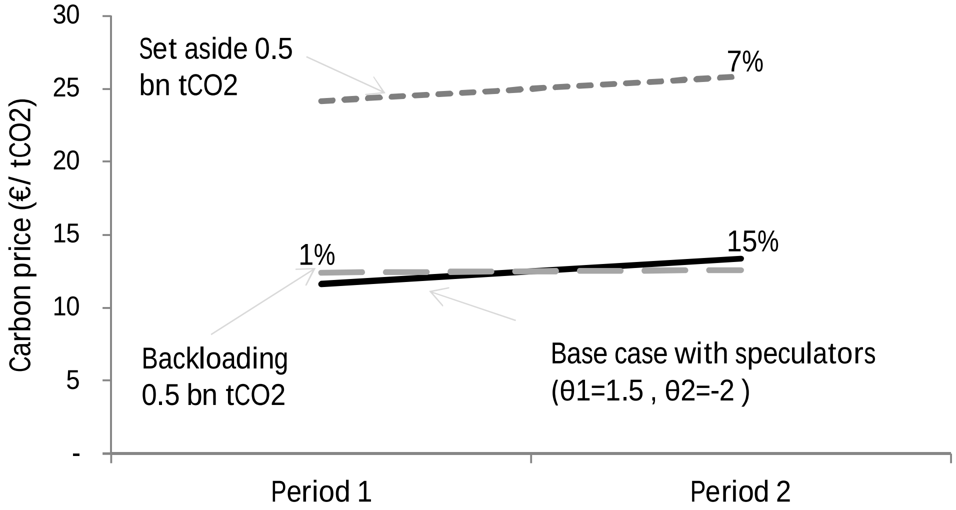
Parameter	Unit	Value
θ_1	Billion t CO_2	0.8
θ_2	Billion t CO_2	-2
β_1, β_2	Billion	0.020
γ	Billion t CO_2	1.5
δ_{CO2}^{s}	%	15
φ		∞
α		0.000000002
ω		1.05

Note: Remaining parameters are as in section 3.

4.3. Illustration of CO_2 hedging, banking and surplus

To illustrate how the model can help to explain recent price development, we apply it to a situation where speculators are needed to balance the market. Figure 3 shows carbon price developments for backloading and a permanent set-aside, as compared to no intervention. In the base case the surplus is 1.7 billion t CO_2 and, thus, exceeds hedging demand by power generators; the remaining parameters are as in Table 4. Therefore, the discount rate between prices in period one and two is 15%.

Figure 3: Impact of policy options on discounting of price expectations (Illustration for small surplus)



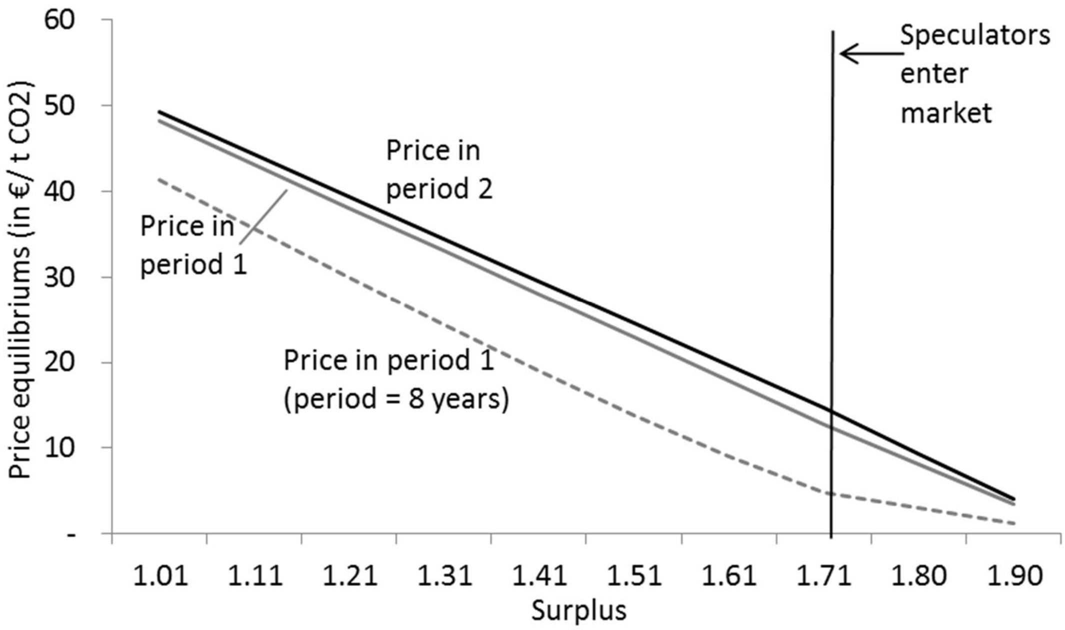
Backloading, for example, 0.5 billion t CO_2 from period one to period two reduces the volume of CO_2 allowances that need to be banked in period one. Thus, prices in period one increase. Since the retained CO_2 allowances add to the surplus in period two, price expectations decrease.

Permanently removing 0.5 billion t CO_2 in period one moves the surplus in the hedging corridor. Prices increase in period one and two. This allows banking at discount rates of 7%.

4.4. Quantification of CO_2 hedging, banking and surplus

To assess the interaction of the CO_2 hedging demand in the power sector with CO_2 banking by speculative investors and CO_2 price dependent emission levels in a two-period mode, we differentiate between the presence of speculators in the market or not. Figure 4 depicts price equilibriums for different surplus volumes in period one. The prices in market equilibrium decrease with the surplus of CO_2 allowances.

Figure 4: Price equilibriums for different surplus levels



With an increasing surplus in period one, the discrepancy between today's price and price expectations widens (solid lines in Figure 4) and hence the discount rates of future prices increase. This discrepancy amplifies if one period does not correspond to one year, but to the eight years (dotted line) and therefore discounting multiplies by eight.

Discount rates of 0 to 10% can be achieved as long as the surplus is between 1.1 and 1.6 billion t CO_2. In this range the surplus matches the hedging demand. As the discount rate increases with increasing supply of allowances in period one to 15%, speculative investors start to enter the market and stabilise the discount rate that applies with further increases of the surplus in period one.

In the EU ETS, the surplus, i.e. the sum of allocated allowances and imported offsets minus emissions is estimated to be 2.4 billion t CO_2 in 2013 and 2.6 billion t CO_2 in 2015 (K. Neuhoff, A. Schopp, R.

Boyd, K. Stelmakh and A. Vasa, 2012). Thus, the surplus exceeds CO_2 hedging by power firms and speculative demand is required to balance the market.

5. Conclusion

First, we model the hedging demand for CO_2 allowances by power firms in the European Emissions Trading System, capturing the insights from 13 interviews. We find two main factors that determine the CO_2 hedging volume: On the one hand, the CO_2 hedging volume depends on the volume of power sold forward, which is a corporate strategy decision that can be adjusted where forward prices deviate significantly from expectations within firms. On the other hand, power firms can hedge with an emphasis on one specific generation technology when this is supported by attractive forward prices - both for carbon and for other fuels. This flexibility can result in adjustments to the CO_2 hedging demand in the corridor of 1.1 to 1.6 billion t by the end of 2012, for discount rates of 0 to 10%.

Second, we model the interactions of CO_2 hedging by power firms, CO_2 banking by speculative investors and CO_2 price dependent emission levels in a two-period framework. With increasing surplus, the discrepancy between today's price and price expectations widens and discount rates of future prices increase. Discount rates of 0 to 10% can be achieved as long as the surplus can be absorbed by CO_2 hedging that ranges between 1.1 and 1.6 billion t CO_2. Once the surplus grows beyond the hedging demand by power firms, speculative investors are needed to balance the market. This points to the value of reducing the surplus of CO_2 allowances in the EU ETS by about 1.3 billion t CO_2 in order to ensure that hedging makes a significant contribution to carbon price stabilisation.

Open to further analysis remains the type of structural reforms needed to guarantee that the surplus stays in the corridor where banking can be pursued at discount rates of 0 to 10%. In particular, uncertainties remain around the variance of actual emissions, the responsiveness of emissions to prices as well as the inflow of international offsets. One way to reduce the exposure to external shocks such as the financial crisis is to determine the upper limit of allowances not for seven years, but rather for shorter time frames. For example, Australia allows for tightening the cap every five years (T. Nelson et al., 2012).

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Appendix

To quantify the annual aggregate CO_2 hedging volume by the power sector, the hedging model can be extended to three generation technologies: coal C, gas G and non-fossils R and to four years ($i = 1, 2, 3, 4$). Year one refers to three years ahead of production and year four is the year of production. Analogously to the two period model, the profit function can be formulated as:

$$\begin{aligned}
&\max_{c_1,g_1,r_1,c_2,g_2,r_2,c_3,g_3,r_3} E(\pi) \\
&= \max_{c_1,g_1,r_1,c_2,g_2,r_2,c_3,g_3,r_3} e_1 * p_1^e(1+\delta_e^m)^4 + e_2 * p_1^e(1+\delta_e^m)^3(1+\delta_e^e)^1 + e_3 \\
&* p_1^e(1+\delta_e^m)^2(1+\delta_e^e)^2 + e_4 * p_1^e(1+\delta_e^m)^1(1+\delta_e^e)^3 \\
&-c_1\left(\frac{p_1^c}{f^c}(1+\delta_c^m)^4 + i_{CO2}^c * p_1^{CO2}(1+\delta_{CO2}^m)^4\right) \\
&-c_2\left(\frac{p_1^c}{f^c}(1+\delta_c^m)^3(1+\delta_c^e)^1 + i_{CO2}^c * p_1^{CO2}(1+\delta_{CO2}^m)^3(1+\delta_{CO2}^e)^1\right) \\
&-c_3\left(\frac{p_1^c}{f^c}(1+\delta_c^m)^2(1+\delta_c^e)^2 + i_{CO2}^c * p_1^{CO2}(1+\delta_{CO2}^m)^2(1+\delta_{CO2}^e)^2\right) \\
&-c_4\left(\frac{p_1^c}{f^c}(1+\delta_c^m)^1(1+\delta_c^e)^3 + i_{CO2}^c * p_1^{CO2}(1+\delta_{CO2}^m)^1(1+\delta_{CO2}^e)^3\right) \\
&-g_1\left(\frac{p_1^g}{f^g}\left(1+\delta_g^m\right)^4 + i_{CO2}^g * p_1^{CO2}(1+\delta_{CO2}^m)^4\right) \\
&-g_2\left(\frac{p_1^g}{f^g}\left(1+\delta_g^m\right)^3\left(1+\delta_g^e\right)^1 + i_{CO2}^g * p_1^{CO2}(1+\delta_{CO2}^m)^3(1+\delta_{CO2}^e)^1\right) \\
&-g_3\left(\frac{p_1^g}{f^g}\left(1+\delta_g^m\right)^2\left(1+\delta_g^e\right)^2 + i_{CO2}^g * p_1^{CO2}(1+\delta_{CO2}^m)^2(1+\delta_{CO2}^e)^2\right) \\
&-g_4\left(\frac{p_1^g}{f^g}\left(1+\delta_g^m\right)^1\left(1+\delta_g^e\right)^3 + i_{CO2}^g * p_1^{CO2}(1+\delta_{CO2}^m)^1(1+\delta_{CO2}^e)^3\right) \\
&-\alpha((\gamma_1 * C - c_1)^2 + (\gamma_2 * C - c_1 - c_2)^2 + (\gamma_3 * C - c_1 - c_2 - c_3)^2 \\
&+ (\gamma_1 * G - g_1)^2 + (\gamma_2 * G - g_1 - g_2)^2 + (\gamma_3 * G - g_1 - g_2 - g_3)^2 + (\gamma_1 * R - r_1)^2 \\
&+ (\gamma_2 * R - r_1 - r_2)^2 + (\gamma_3 * R - r_1 - r_2 - r_3)^2)
\end{aligned} \tag{A1}$$

As in the two period model, the profit function is subject to the following constraints:

$$c_4 = C - c_1 - c_2 - c_3 \geq 0 \tag{A2}$$

$$g_4 = G - g_1 - g_2 - g_3 \geq 0 \tag{A3}$$

$$r_4 = R - r_1 - r_2 - r_3 \geq 0 \tag{A4}$$

$$c_1, c_2, c_3, g_1, g_2, g_3, r_1, r_2, r_3 \geq 0 \tag{A5}$$

From the associated Lagrangian, we derive the first order (Karush–Kuhn–Tucker) conditions:

$$\begin{aligned}
\frac{\partial L}{\partial c_1} &= p_1^e((1+\delta_e^m)^4 - (1+\delta_e^m)^1(1+\delta_e^e)^3) - \frac{p_1^c}{f^c}((1+\delta_c^m)^4 - (1+\delta_c^m)^1(1+\delta_c^e)^3) - i_{CO2}^c \\
&* p_1^{CO2}((1+\delta_{CO2}^m)^4 - (1+\delta_{CO2}^m)^1(1+\delta_{CO2}^e)^3) + 2\alpha(\gamma_1 * C - c_1) + 2\alpha(\gamma_2 * C - c_1 - c_2) \\
&+ 2\alpha(\gamma_3 * C - c_1 - c_2 - c_3) - \lambda_1 = 0
\end{aligned} \tag{A6}$$

$$\frac{\partial L}{\partial c_2} = p_1^e((1+\delta_e^m)^3(1+\delta_e^e)^1 - (1+\delta_e^m)^1(1+\delta_e^e)^3) - \frac{p_1^c}{f^c}((1+\delta_c^m)^3(1+\delta_c^e)^1 - (1+\delta_c^m)^1(1+\delta_c^e)^3) - i_{CO2}^c * p_1^{CO2}((1+\delta_{CO2}^m)^3\,(1+\delta_{CO2}^e)^1 - (1+\delta_{CO2}^m)^1\,(1+\delta_{CO2}^e)^3) + 2\alpha(\gamma_2 * C - c_1 - c_2) + 2\alpha(\gamma_3 * C - c_1 - c_2 - c_3) - \lambda_1 = 0 \quad \text{(A7)}$$

$$\frac{\partial L}{\partial c_3} = p_1^e((1+\delta_e^m)^2(1+\delta_e^e)^2 - (1+\delta_e^m)^1(1+\delta_e^e)^3) - \frac{p_1^c}{f^c}((1+\delta_c^m)^2(1+\delta_c^e)^2 - (1+\delta_c^m)^1(1+\delta_c^e)^3) - i_{CO2}^c * p_1^{CO2}((1+\delta_{CO2}^m)^2\,(1+\delta_{CO2}^e)^2 - (1+\delta_{CO2}^m)^1\,(1+\delta_{CO2}^e)^3) + 2\alpha(\gamma_3 * C - c_1 - c_2 - c_3) - \lambda_1 = 0 \quad \text{(A8)}$$

$$\frac{\partial L}{\partial g_1} = p_1^e((1+\delta_e^m)^4 - (1+\delta_e^m)^1(1+\delta_e^e)^3) - \frac{p_1^g}{f^g}\left((1+\delta_g^m)^4 - (1+\delta_g^m)^1(1+\delta_g^e)^3\right) - i_{CO2}^g * p_1^{CO2}((1+\delta_{CO2}^m)^4 - (1+\delta_{CO2}^m)^1\,(1+\delta_{CO2}^e)^3) + 2\alpha(\gamma_1 * G - g_{14}) + 2\alpha(\gamma_2 * G - g_1 - g_2) + 2\alpha(\gamma_3 * G - g_1 - g_2 - g_3) - \lambda_2 = 0 \quad \text{(A9)}$$

$$\frac{\partial L}{\partial g_2} = p_1^e((1+\delta_e^m)^3(1+\delta_e^e)^1 - (1+\delta_e^m)^1(1+\delta_e^e)^3) - \frac{p_1^g}{f^g}\left((1+\delta_g^m)^3(1+\delta_g^e)^1 - (1+\delta_g^m)^1(1+\delta_g^e)^3\right) - i_{CO2}^g * p_1^{CO2}((1+\delta_{CO2}^m)^3\,(1+\delta_{CO2}^e)^1 - (1+\delta_{CO2}^m)^1\,(1+\delta_{CO2}^e)^3) + 2\alpha(\gamma_2 * G - g_1 - g_2) + 2\alpha(\gamma_3 * G - g_1 - g_2 - g_3) - \lambda_2 = 0 \quad \text{(A10)}$$

$$\frac{\partial L}{\partial g_3} = p_1^e((1+\delta_e^m)^2(1+\delta_e^e)^2 - (1+\delta_e^m)^1(1+\delta_e^e)^3) - \frac{p_1^g}{f^g}\left((1+\delta_g^m)^2(1+\delta_g^e)^2\right) - i_{CO2}^g * p_1^{CO2}((1+\delta_{CO2}^m)^2\,(1+\delta_{CO2}^e)^2 - (1+\delta_{CO2}^m)^1\,(1+\delta_{CO2}^e)^3) + 2\alpha(\gamma_3 * G - g_1 - g_2 - g_3) - \lambda_2 = 0 \quad \text{(A11)}$$

$$\frac{\partial L}{\partial r_1} = p_1^e((1+\delta_e^m)^4 - (1+\delta_e^m)^1(1+\delta_e^e)^3) + 2\alpha(\gamma_1 * R - r_{14}) + 2\alpha(\gamma_2 * R - r_1 - r_2) + 2\alpha(\gamma_2 * R - r_1 - r_2 - r_3) - \lambda_3 = 0 \quad \text{(A12)}$$

$$\frac{\partial L}{\partial r_2} = p_1^e((1+\delta_e^m)^3(1+\delta_e^e)^1 - (1+\delta_e^m)^1(1+\delta_e^e)^3) + 2\alpha(\gamma_2 * R - r_1 - r_2) + 2\alpha(\gamma_2 * R - r_1 - r_2 - r_3) - \lambda_3 = 0 \quad \text{(A13)}$$

$$\frac{\partial L}{\partial r_3} = p_1^e((1+\delta_e^m)^2(1+\delta_e^e)^2 - (1+\delta_e^m)^1(1+\delta_e^e)^3) + 2\alpha\left(\gamma_2 * R - r_1 - r_2 - r_3\right) - \lambda_3 = 0 \quad \text{(A14)}$$

$$\frac{\partial L}{\partial \lambda_1} = C - c_1 - c_2 - c_3 \geq 0, \qquad \lambda_1 \geq 0, \qquad (C - c_1 - c_2 - c_3)\lambda_1 = 0 \quad \text{(A15)}$$

$$\frac{\partial L}{\partial \lambda_2} = G - g_1 - g_2 - g_3 \geq 0, \qquad \lambda_2 \geq 0, \qquad \left(G - g_1 - g_2 - g_3\right)\lambda_2 = 0 \quad \text{(A16)}$$

$$\frac{\partial L}{\partial \lambda_3} = R - r_1 - r_2 - r_3 \geq 0, \qquad \lambda_3 \geq 0, \qquad (R - r_1 - r_2 - r_3)\lambda_3 = 0 \quad \text{(A17)}$$

Solving for the volumes of coal, gas and non-fossils in the assumption that expectations for power, coal and gas match forward contracts for these commodities yields:

$$c_1 = \frac{1}{2\alpha} * i_{CO2}^c * p_1^{CO2}(-(1+\delta_{CO2}^m)^4 + (1+\delta_{CO2}^m)^3\,(1+\delta_{CO2}^e)^1) + \gamma_1 * C \quad \text{(A18)}$$

$$c_2 = \frac{1}{2\alpha} * i^c_{CO2} * p_1^{CO2}((1 + \delta^m_{CO2})^4 - 2(1 + \delta^m_{CO2})^3\,(1 + \delta^e_{CO2})^1 + (1 + \delta^m_{CO2})^2\,(1 + \delta^e_{CO2})^2)$$ (A19)

$$-(\gamma_1 - \gamma_2)\,C$$

$$c_3 = \frac{1}{2\alpha} * i^c_{CO2}$$ (A20)

$$* p_1^{CO2}((1 + \delta^m_{CO2})^3\,(1 + \delta^e_{CO2})^1 - 2(1 + \delta^m_{CO2})^2\,(1 + \delta^e_{CO2})^2 + (1 + \delta^m_{CO2})^1\,(1 + \delta^e_{CO2})^3) + \frac{\lambda_1}{2\alpha}$$
$$-(\gamma_2 - \gamma_3)\,C$$

$$g_1 = \frac{1}{2\alpha} * i^g_{CO2} * p_1^{CO2}(-(1 + \delta^m_{CO2})^4 + (1 + \delta^m_{CO2})^3\,(1 + \delta^e_{CO2})^1) + \gamma_1 * G$$ (A21)

$$g_2 = \frac{1}{2\alpha} * i^g_{CO2} * p_1^{CO2}((1 + \delta^m_{CO2})^4 - 2(1 + \delta^m_{CO2})^3\,(1 + \delta^e_{CO2})^1 + (1 + \delta^m_{CO2})^2\,(1 + \delta^e_{CO2})^2)$$ (A22)

$$-(\gamma_1 - \gamma_2)G$$

$$g_3 = \frac{1}{2\alpha} * i^g_{CO2}$$ (A23)

$$* p_1^{CO2}((1 + \delta^m_{CO2})^3\,(1 + \delta^e_{CO2})^1 - 2(1 + \delta^m_{CO2})^2\,(1 + \delta^e_{CO2})^2 + (1 + \delta^m_{CO2})^1\,(1 + \delta^e_{CO2})^3) + \frac{\lambda_2}{2\alpha}$$
$$-(\gamma_2 - \gamma_3)G$$

The aggregate CO_2 hedging demand by the end of 2012 amounts to:

$$H = \left(3 * c_1 + 2 * c_2 + c_3\right) i^c_{CO2} + \left(3 * g_1 + 2 * g_2 + g_3\right) i^g_{CO2}$$ (A24)

$$= \left(\frac{1}{2\alpha} * i^c_{CO2} * p_1^{CO2}(-(1 + \delta^m_{CO2})^4 + (1 + \delta^m_{CO2})^1\,(1 + \delta^e_{CO2})^3) + \frac{\lambda_1}{2\alpha} + (\gamma_1 + \gamma_2 + \gamma_3)\,C\right) i^c_{CO2}$$
$$+ \left(\frac{1}{2\alpha} * i^g_{CO2} * (-(1 + \delta^m_{CO2})^4 + (1 + \delta^m_{CO2})^1\,(1 + \delta^e_{CO2})^3) + \frac{\lambda_2}{2\alpha} + (\gamma_1 + \gamma_2 + \gamma_3)\,G\right) i^g_{CO2}$$