Can banking CO_2 allowances ensure inter-temporal efficiency?

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The banking of CO_2 allowances in cap-and-trade schemes allows surplus allowances to be transferred to future years. Inter-temporal efficiency is ensured, providing market participants bank the allowances in the expectation of modest price increases. However, as the surplus of allowances in the European Union Emission Trading Scheme has accumulated, market participants are reporting that they only hold surplus CO_2 allowances at modest discount rates to the extent that they need these allowances in order to hedge future CO_2 exposure. Once their hedging demand is exhausted, the remaining surplus needs to be banked as speculative investment. (New) market participants may speculate if high discount rates compensate them for the risk of uncertain carbon price developments. However, highly discounted carbon price expectations can delay low carbon investment and thus jeopardize inter-temporal efficiency. This raises the question as to what volume of surplus allowances can be hedged in order to ensure inter-temporal efficiency. In an attempt to answer this question we model hedging demand in the power sector as a function of the carbon price structure and risk management strategies reported by power firms in interviews. This partial equilibrium analysis is then integrated into a two period CO_2 supply and demand model with emitting firms, hedging by power firms and banking of allowances by speculative investors.

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

1. Introduction

In cap-and-trade schemes, carbon allowance caps are fixed several years in advance and do not respond to variations in demand. Banking allows market participants to hold allowances for future use, ensuring inter-temporal efficiency in ideal circumstances (Cronshaw and Kruse, 1996; Rubin, 1996). In the European Union Emissions Trading System (EU ETS), power firms are the main actors banking. This paper examines the role of power firms' hedging behaviour in providing inter-temporal flexibility to the system.

Banking is a central pillar in cap-and-trade schemes. For the SO_2 US Acid Rain Program Ellerman et al. (2007) show that firms banked an efficient volume that allowed for reducing the overall abatement cost of the scheme. At the end of the first EU ETS trading period, supply exceeded demand, leading to a price crash due to provisions prohibiting banking (Alberola and Chevallier, 2009; Chevallier, 2011). In the second trading period a surplus of more than two billion tonnes of CO_2 accumulated (EU, 2012c). However, the carbon price in the EU ETS did not drop to zero at the end of the second trading period because market participants were allowed to bank surplus allowances. In other words, banking can help stabilise carbon prices and contribute to inter-temporal efficiency.

Evidence from other commodity markets (Bessembinder, 1992; Wang, 2001) as well as interviews with EU ETS market participants (Neuhoff et al., 2012) show that risk return requirements vary across the different types of actors and the strategy which motivates the actors to bank. There are three underlying motives explaining the banking of allowances, according to Bailey's (2005) analysis of financial markets: hedging, speculation, and arbitrage. Hedgers buy or sell commodities or forward contracts to protect against input or product price changes. Speculators buy or sell commodities or forward contracts as an investment that meets their risk-return requirements. Arbitrageurs aim to benefit from price differentials between spot and forward prices. As allowances can be banked at zero cost, banks can offer forward contracts for CO_2 allowances (for example to power firms) at the price at which they acquire allowances in the spot market, times the opportunity costs of capital over the duration of the forward contract. This is reflected in the forward contract prices that are usually traded 3 - 4 years ahead. In the second trading period future contracts were generally traded with a premium of about 3 - 5 percent per year (EEX, 2012). Any additional surplus requires market participants that acquire allowances not for hedging but as speculative investment. However, market participants consider investments in CO_2 allowances as a risky commodity investment, and therefore only pursue it if they expect an annual rate of return exceeding 10 – 15 percent (Neuhoff et al., 2012). The resulting steep carbon price pathways illustrated in Figure 1 can reduce inter-temporal efficiency of cap-and trade schemes. Hence, the flexibility of the hedging volume (given fixed supply of allowances) determines the inter-temporal flexibility of emission trading schemes and the stability of carbon prices in such schemes.

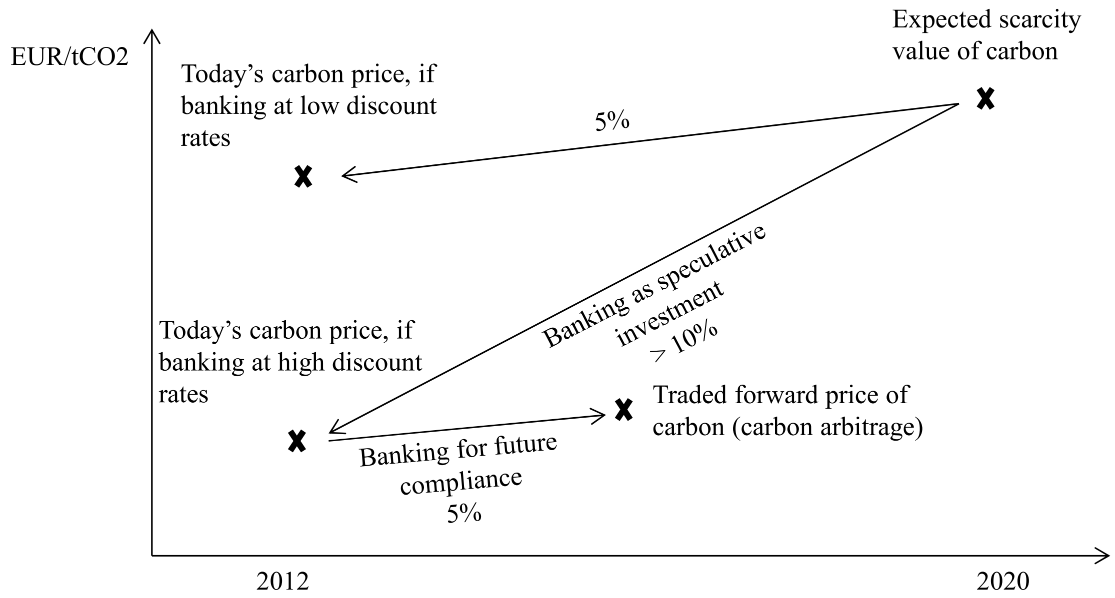

Figure1: Conceptual framework of banking types and discount rates

This is the starting point of our analysis. We model the different motives to bank allowances in a partial equilibrium framework, accounting for emitters, hedgers and speculators. In order to model the flexibility of the hedging volume with CO_2 allowances by power firms, we conducted 13 semi-structured interviews on corporate risk management procedures. On the one hand, the CO_2 intensity of power generation changes with the deployment of renewables as well as with fuel and carbon prices. As a result the volume of allowances required to hedge future power generation also changes. On the other hand, power firms can choose to adjust the volume of power they sell on forward contracts, and can decide to use coal, gas, or low carbon generation to back forward sales. Power firms reported that the hedging volume is adjusted according to deviations of forward prices from firms' expectations. If a power firm expects the CO_2 price to significantly exceed the price at which forward contracts are traded, then it may increase the total contracted volumes of power forward sales and also increase the contracted volumes of carbon intensive (fossil) generation assets (and the associated CO_2 allowances) used to hedge price changes. According to our estimates such individual adjustments could result in an overall CO_2 hedging volume in the range of 1.1 to 1.7 billion allowances by the end of 2012 at discount rates of carbon price expectations between 0 to 10 percent.

As the cumulative surplus in the EU ETS exceeds the hedging volume by power firms, we further model the impact of CO_2 banking by speculative investors. In so doing, we demonstrate carbon price dynamics given different types of banking and evaluate policy options to back-load or set-aside surplus allowances. In our modelling framework, the discrepancy between forward prices and price expectations widens gradually, as the surplus increases.

The paper is structured as follows: Section 2 models the CO_2 allowance volumes European power generators use to hedge forward power sale. Section 3 integrates CO_2 hedging into a market equilibrium model with emitting firms and CO_2 banking by speculative investors in order to illustrate the carbon price dynamics given different types of actors who bank surplus allowances. Section 4 draws conclusions.

2. Hedging with allowances by power firms

We develop a model that allows for a quantification of the hedging volume of carbon emission allowances. To inform the model, we conducted interviews with power firms in 2012. Following purposive sampling we contacted the main power firms in Western Europe, since, unlike most power firms in Eastern Europe, they do not receive free allowances from 2013 onwards. Hedging experts from 13 power firms responded, accounting for 56 percent of European power production (Badenova, 2011; DONG Energy, 2011; EDF, 2011; EnBW, 2011; Enel, 2011; Enercity, 2011; GDF Suez, 2011; Iberdrola, 2011; MVV Energie, 2010; RWE, 2011; Stadtwerke München, 2011; Statkraft, 2011; Vattenfall, 2011). The interviews covered three aspects:

- the main factors that determine hedging with carbon emission allowances,
- the metrics to formulate the hedging schedule, and
- thresholds to deviate from the hedging schedule.

2.1 Two-period model of hedging by power firms

In the interviews, power firms reported that they sell power several years ahead of production in order to reduce their exposure to price risks and profit volatility from power production. To lock in profits from the power sold in advance, firms also acquire the input factors, namely coal, gas, and carbon emission allowances or contracts that secure the price for these inputs.

We use a two-period model to illustrate the mechanics of the partial equilibrium model, and subsequently present results calibrated to the empirical contracting strategy, therefore allowing for up to four years of forward contracting.

In period one of the model, the years prior to production, the firm sells part of the power E that will be produced in period two on forward contracts e_1 and, at the same time, acquires part of the coal C and gas G (and the associated emission allowances) used for power production on forward contracts c_1, g_1. In period two, the year of production, the firm contracts the remaining power to match projected generation $E - e_1$ and acquires the required input factors or contracts that secure the input prices. The model focuses on the forward contracting strategy, as this has the largest impact on total hedging demand.

In the interviews, it was also reported that the volume and the period for which power is sold forward is a corporate strategy decision. In the model therefore the firm formulates a hedging schedule, based on its expected generation portfolio: γ_1 percent of power is sold in period one and γ_2 percent is sold in period two. Several power firms reported that they prefer to hedge uniformly across the portfolio of their generation assets rather than hedging with a strong emphasis on one specific generation technology. Hence, the hedging schedule specifies that in parallel the firm buys in proportion to its generation portfolio γ_1 percent of coal C and gas G in period one and γ_2 percent in period two. To reflect the preference to hedge across the portfolio, deviations from this proportional hedging schedule are included with a quadratic penalty term, where α can be interpreted as the internal transaction cost.

Hedging schedule:

$$\alpha((\gamma_1\, C - c_1)^2 + (\gamma_1\, G - g_1)^2). \tag{1}$$

However, power firms reported that they can deviate from their hedging schedule, if it is attractive for them. In the model, power firms can adjust the hedging volume**,** when firms' expectations about future energy and carbon prices differ from forward contract prices in the market. For example, if the forward price at which power can be sold forward in year one p_1^e deviates from the power price that the firm expects to materialise in period two $E(p_2^e)$ then it can increase the volume of power sold in period one e_1 and decrease the power sold in period two e_2. Therefore, in period one the firm considers the revenues from forward sales in period one and the remaining short-term sales in year two.

Similarly, if the carbon price $E(p_2^{CO2})$ is expected to increase above the price at which forward contracts are traded in period one p_1^{CO2}, power firms have an incentive to prioritise hedging future power sales with generation by carbon intensive assets in period one, e.g. coal c_1 (rather than gas g_1). To avoid risk exposure on the input factors, the firm chooses the volume of allowances bought on forward contracts to match the power production from coal and gas sold on forward contracts. 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}. Hence, if more coal is used to hedge future power sales in period one, the hedging demand for CO_2 increases in period one (and decreases in period two).

Hedging flexibility:

$$e_1\, p_1^e + (E - e_1\,)\, E(p_2^e) - \left[c_1\, \left(\frac{p_1^c}{f^c} + i_{CO2}^c\, p_1^{CO2}\right) + (C - c_1\,)\left(\frac{E(p_2^c)}{f^c} + i_{CO2}^c E(p_2^{CO2})\right)\right] - \left[g_1\, \left(\frac{p_1^g}{f^g} + i_{CO2}^g\, p_1^{CO2}\right) + (G - g_1\,)\left(\frac{E(p_2^g)}{f^g} + i_{CO2}^g\, E(p_2^{CO2})\right)\right] \tag{2}$$

where f^c represents the thermal efficiency of the coal-fired power plants and f^g the thermal efficiency of the gas plants.

In the interviews, it was also reported that open positions in power sales are avoided. This implies that the power forward sale in period one must be matched by forward contracts where coal and gas are required to produce the power $e_1 = c_1 + g_1$.

The power firm chooses the contract volume of coal and gas in year one, so as to maximise its objective function based on the two factors, namely hedging schedule and hedging flexibility, (combining equations (1) to (2) and substituting $e_1$by $c_1 + g_1$):

$$\begin{aligned}&\max_{c_1,g_1} -(c_1+g_1)(E(p_2^e)-p_1^e)+(C+G)\,E(p_2^e)+c_1\left(\frac{E(p_2^c)-p_1^c}{f^c}+i_{CO2}^c(E(p_2^{CO2})-p_1^{CO2})\right)-\\&C\left(\frac{E(p_2^c)}{f^c}+i_{CO2}^c\,E(p_2^{CO2})\right)+g_1\left(\frac{E(p_2^g)-p_1^g}{f^g}+i_{CO2}^g(E(p_2^{CO2})-p_1^{CO2})\right)-\\&G\left(\frac{E(p_2^g)}{f^g}+i_{CO2}^g\,E(p_2^{CO2})\right)-\alpha((\gamma_1\,C-c_1)^2+(\gamma_1\,G-g_1)^2).\end{aligned} \tag{3}$$

The objective function is subject to the constraint that the firm does not hedge more than it can generate:

$$C-c_1\geq 0,\qquad G-g_1\geq 0,\qquad c_1,\,g_1\geq 0. \tag{4}$$

The corresponding first order conditions of the Lagrangian L are the following:

$$\frac{\partial L}{\partial c_1}=-(E(p_2^e)-p_1^e)+\frac{E(p_2^c)-p_1^c}{f^c}+i_{CO2}^c(E(p_2^{CO2})-p_1^{CO2})+2\alpha\,(\gamma_1\,C-c_1)-\lambda_1=0, \tag{5}$$

$$\frac{\partial L}{\partial g_1}=-(E(p_2^e)-p_1^e)+\frac{E(p_2^g)-p_1^g}{f^g}+i_{CO2}^g(E(p_2^{CO2})-p_1^{CO2})+2\alpha\,(\gamma_1\,G-g_1)-\lambda_2=0, \tag{6}$$

$$\frac{\partial L}{\partial \lambda_1}=\ C-c_1\geq 0, \tag{7}$$

$$\frac{\partial L}{\partial \lambda_2}=\ G-g_1\geq 0, \tag{8}$$

$$c_1,\,g_1\geq 0. \tag{9}$$

In our subsequent analysis we focus on the demand and prices for forward contracts for carbon emission allowances and assume that expectations for prices of the remaining commodities, namely power, coal and gas match forward contracts prices. With $\lambda_1=0$, $\lambda_2=0$ and $C-c_1\geq 0$, $G-g_1\geq 0$ (internal solution) equations (5) and (6) can be rewritten as:

$$c_1\ =\frac{1}{2\,\alpha}\,i_{CO2}^c(E(p_2^{CO2})-p_1^{CO2})+\gamma_1\,C, \tag{10}$$

$$g_1\ =\frac{1}{2\,\alpha}\,i_{CO2}^g(E(p_2^{CO2})-p_1^{CO2})\ +\gamma_1\,G. \tag{11}$$

From the optimal coal and gas volumes contracted in period one (10, 11) follows the hedging volume of allowances acquired in period one h_1 to hedge production in period two:

$$\begin{aligned}h_1\ &=c_1\ i_{CO2}^c+g_1\ i_{CO2}^g\\&=\left(\frac{1}{2\,\alpha}\,i_{CO2}^c(E(p_2^{CO2})-p_1^{CO2})+\gamma_1\,C\right)i_{CO2}^c+\left(\frac{1}{2\,\alpha}\,i_{CO2}^g(E(p_2^{CO2})-p_1^{CO2})\ +\gamma_1\,G\right)i_{CO2}^g.\end{aligned} \tag{12}$$

Equation (12) reduces to the hedging schedule $\left(\gamma_1\, C\, i_{CO2}^{c} + \gamma_1\, G\, i_{CO2}^{g}\right)$, if expectations of future carbon prices match forward contracts for allowances. If expectations are higher $(E(p_2^{CO2}) = (1 + \delta_{CO2}^{e})\, p_1^{CO2} > p_1^{CO2})$, power firms deviate from their hedging schedule and contract greater volumes of coal and gas. In this case, power firms acquire more allowances today and less later on; leading to an increase in the hedging demand for allowances in the short-term.

2.2 Parameterisation of CO_2 hedging volume

To quantify the CO_2 hedging volume by the power sector, we extend the model to allow for forward contracting up to four years prior to production $(t{:}\, 1,2,3,4)$ and to three generation technologies: coal C, gas G and non-fossils R. As with 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 quantify, bottom-up, the hedging volume in the power sector, we use the hedging schedule of Western European power firms weighted by their power share. Data on the actual volume of allowances that firms hold for hedging or speculative purposes is released with a five year delay (EUTL), whilst data on the volume of financial contracts used for hedging are not available. We therefore derive the hedging schedules from their energy contracting volumes. Three power firms disclosed their hedging schedule in their 2010 annual reports (E.ON, 2011; RWE, 2011; Vattenfall, 2011). For the remaining firms, we rely on a survey conducted by Eurelectric (2010). Table 1 shows that the hedging need for allowances has increased since 2010 because many power firms acquire their allowances at auction and, since 2013, no longer receive them free of charge. The resulting schedule to hedge power is: 20 percent of power production three years ahead, 46 percent two years ahead, 84 percent one year ahead of production, i.e. 150 percent of the annual emissions by the end of 2012. This calculation excludes hedging needs from Eastern European utilities since most of the new EU Member States allow for continued free allocation of allowances to existing power plants in the third trading period, thus largely avoiding the need for power firms to acquire allowances for hedging purposes (EU, 2012b). Official reports and interview results led us to assume that in Spain utilities only hedge one year ahead.

Table 1: Average hedging schedule in percent

Year i **Year j**	**2010**	**2011**	**2012**
2013	20	26	38
2014	0	20	26
2015	0	0	20
Percent of power hedged in year i for years j	20	46	84

The parameters used to quantify the hedging volume in the power sector are summarised in Table 2

Table 2: Parameter assumptions of CO_2 hedging model

Parameter	**Unit**	**Value**	**Source**
p_1^e	Euro/ MWh	51.40	EEX (2012), ∅ price Jan-May 2012
p_1^c	Euro/ MWh	12.10	
p_1^g	Euro/ MWh	26.90	
C	GWh	639,103	E.ON (2011), EDF(2011) EnBW (2011), Enel (2011), Eurostat (2012), GDF Suez (2011), Iberdrola (2011), RWE (2011), Statkraft (2011), Vattenfall (2011)
G	GWh	718,991	
R	GWh	1,295,260	
γ_1	Percent	20	E.ON (2011), Eurelectric (2010), RWE (2011), Vattenfall (2011)
γ_2	Percent	46	
γ_3	Percent	84	
i_{CO2}^c	t CO_2/ MWh	0.96	IPCC (2006)
i_{CO2}^g	t CO_2/ MWh	0.41	
f^c	Percent	40.80	IEA et al. (2010)
f^g	Percent	55.10	

To calibrate the penalty function for deviations from the hedging schedule α, we use information from the interviews. Some power firms reported that it requires a difference of one to four Euro/tonne of CO_2 between forward contract prices and the firm's or analyst's carbon price expectation to trigger a deviation from the hedging schedule. Furthermore, it was reported that such deviations are in the order of 10 percent. We therefore set the internal transaction cost parameter α such that if firms expect carbon prices to be one Euro higher than the price at which carbon forward contracts are traded, they increase their hedging volume by 10 percent. We also consider how the hedging volume changes when carbon prices are lower or α is set at a higher value, so that firms require a higher price incentive to deviate from their hedging schedule (Table 3).

Table 3: Sensitivity analysis

Parameter	**Unit**	Base case	2012 CO_2 price	Lower sensitivity
α	Euro/ GWh	0.00000845 →1 Euro/ t CO_2, Δ10 percent hedging	0.00000845	0.0000171 →2 Euro/ t CO_2, Δ10 percent hedging
p_1^{CO2}	Euro/ t CO_2	20	7.5 ∅ Jan-May2012	20

2.3 Quantification of CO_2 hedging volume

The hedging model is formulated as a mixed complementarity problem and programmed in GAMS. We use it to calculate the hedging volume of the power sector for different carbon price expectations. Figure 2 shows that CO_2 hedging can potentially provide some flexibility to the supply-demand balance of the EU ETS. If power firms expect that carbon prices increase with the opportunity cost of capital for banks selling forward contracts (i.e., $\delta_{CO2}^{m} = \delta_{CO2}^{e} = 5$ percent), then they follow the hedging schedule, set at 20 percent three years ahead, 46 percent two years ahead and 84 percent one year ahead of production. This corresponds to a hedging volume of 1.4 billion tonnes of CO_2 by the end of 2012 or 150 percent of the annual emissions.

If market participants expect carbon prices to be flatter than reflected in forward contract prices (e.g. $\delta_{CO2}^{e} = 0$ percent, $\delta_{CO2}^{m} = 5$ percent), the hedging volume will decrease below the hedging schedule. Equally, the hedging volume will increase above the hedging schedule, if power firms expect that carbon prices will increase faster than reflected in forward contract prices (e.g. $\delta_{CO2}^{e} = 10$ percent). The CO_2 hedging volume ranges from 1.1 to 1.7 billion tonnes of CO_2 by the end of 2012, assuming a current forward price of 20 Euro per tonne of CO_2 and expected carbon price increases of 0 - 10 percent (error bars in Figure 2).

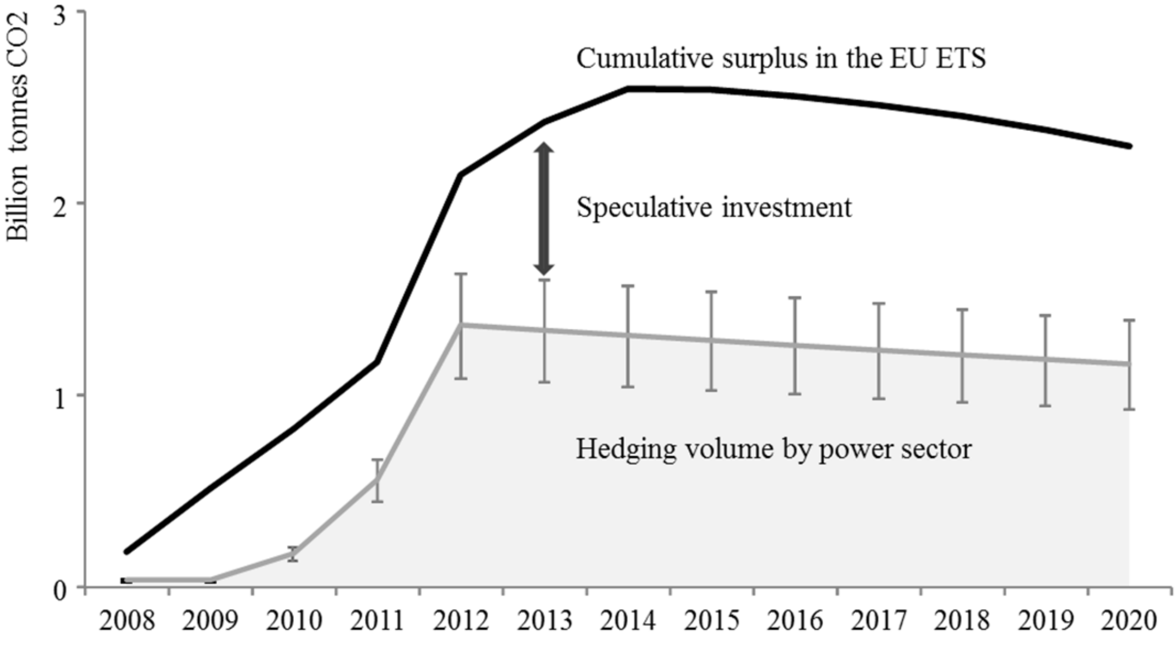

Figure 2: Surplus of CO_2 allowances and hedging volume

Sources: Based on Neuhoff et al. (2012) and data sources listed in Table 2

However, carbon prices have dropped in 2011 and amounted in 2012 on average to 7-7.5 Euro. Assuming a carbon price of 7.5 Euro per tonne of CO_2, the hedging volume ranges from CO_2 volume 1.3 to 1.5 billion tonnes (black dotted line in Figure 3). Hence, with lower carbon prices, the flexibility of the power sector to adjust the hedging volume decreases.

To examine the sensitivity of the results, we also consider a higher level of α. This means firms are less sensitive, as they need to expect that prices will be at two Euro above forward prices in order for them to increase their hedging volume by 10 percent. In this case the hedging volume ranges from 1.2 to 1.5 billion tonnes (grey solid line). In general, the higher the firm's internal transaction costs in responding to arbitrage opportunities are, the lower the adjustment of the hedging volume to price expectations will be.

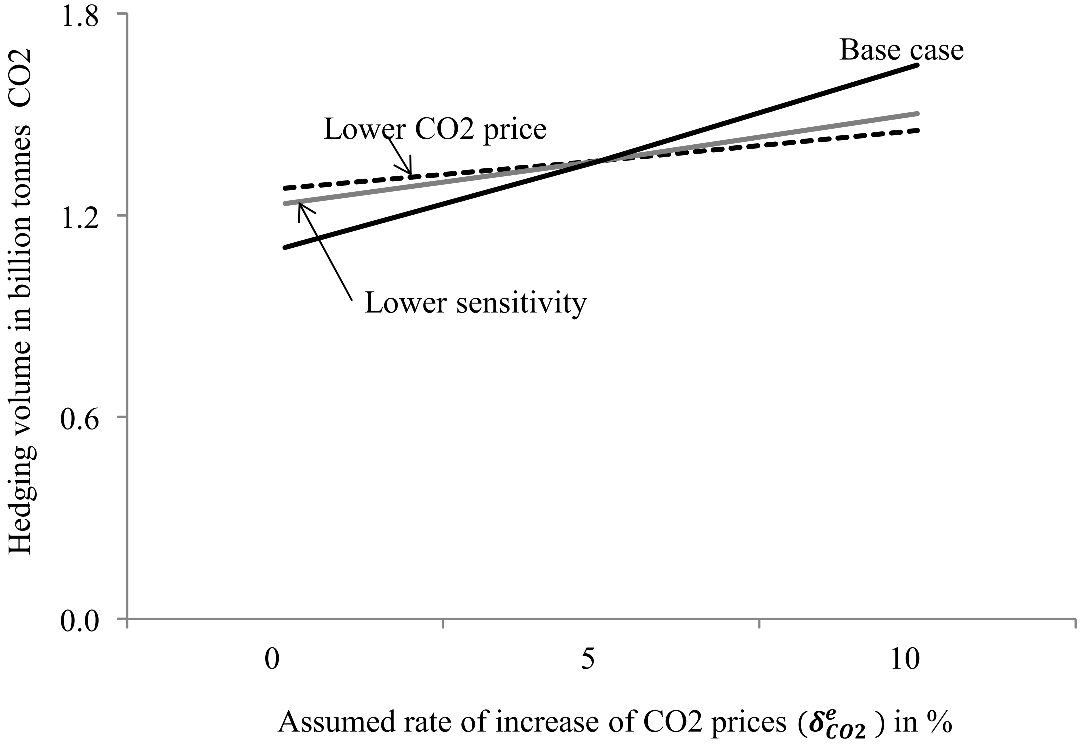

Figure 3: Flexibility in CO_2 hedging volume for different expected discount rates

3. CO_2 market equilibrium with emitters, hedgers and speculators

Hedging by power firms can be satisfied by banks that provide forward contracts. If banks back these contracts with physical allowances, they do not carry the price risk and thus can offer such contracts at the cost of capital. This behaviour is reflected in the implied discount rate by comparing forward contract prices to current spot prices. In the second trading period future contracts were generally traded with a premium of about 3 - 5 percent per year (EEX, 2012).

The supply of allowances in the EU ETS exceeds the demand by emitters to meet current compliance obligations and the hedging volume by power firms to meet future compliance obligations. Additional surplus allowances need to be banked as speculative investment.

Allowances have many features common to commodities like metals or fuels (except zero storage cost). This suggests that market participants have similar return requirements for banking EU ETS allowances as speculative investment as they have for investing in other commodities. According to evidence from other commodity markets (Bessembinder, 1992; Wang, 2001) as well as interviews with EU ETS market participants (Neuhoff et al., 2012) the annual rate of return to compensate for carbon price risks are in the order of 10 - 15 percent. If the carbon price has to appreciate by 10 percent (or more) year-on-year to attract investors in banking allowances, then long term price expectations are discounted higher and current prices are lower.

We model the effect of banking at different discount rates for a two-period framework with carbon price dependent emitting firms, hedgers and speculators.

3.1 Two-period model of CO$_2$ emitters, hedgers and speculators

We assume that in each period the allocation of allowances is fixed and that the emissions decrease with an increase in allowance prices p_t^{CO2} according to the emission responsiveness parameter β_t. As a result the net surplus $Q_t^{surplus}$ of allowances in period t increases with increasing prices:

$$Q_t^{surplus} = \theta_t + \beta_t \, p_t^{CO2} \tag{13}$$

The unused allowances from period one $Q_t^{surplus}$ can be banked for usage in period two. Demand for these allowances derives from hedgers Q^h and speculators Q^s . Hedgers acquire allowances to secure the prices of future production as formulated in equation (14). As in the four period model, we assume that banks offer forward contracts at forward market prices that increase at a fixed rate δ_{CO2}^m between the periods of years n. Hedgers can acquire these forward contracts and thus avoid using cash. If they expect that prices $E(p_2^{CO2})$ increase at a higher rate than reflected in the market $p_1^{CO2}(1+\delta_{CO2}^m)^n$, they hedge more in period one and less in period two and vice versa:

$$Q_1^h = \left(\frac{1}{2\,\alpha}\, i_{CO2}^c \left(\frac{E(p_2^{CO2})}{(1+\delta_{CO2}^m)^n} - p_1^{CO2}\right) + \gamma\, C\right) i_{CO2}^c + \left(\frac{1}{2\,\alpha}\, i_{CO2}^g \left(\frac{E(p_2^{CO2})}{(1+\delta_{CO2}^m)^n} - p_1^{CO2}\right) + \gamma\, G\right) i_{CO2}^g \tag{14}$$

Speculators do hold allowances not to hedge future production, but to make profit by betting that the price will develop in a certain way. They have an incentive to acquire allowances 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, $\delta_{CO2}^e = \sqrt[n]{E(p_2^{CO2})/p_1^{CO2}} - 1$. Thus, the speculative demand can be formulated as a maximum function:

$$Q_1^s = \max(\varphi\,(\delta_{CO2}^e - \delta_{CO2}^s), 0) \tag{15}$$

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 towards infinity a fixed large volume of speculative demand is available at return rate δ_{CO2}^{s}.

Equations (14) and (15) form the overall demand in period one. Equalising demand to the cumulative market surplus yields the equilibrium price. The market equilibrium in period one is:

$$Q_1^{surplus} - Q_1^h - Q_1^s = 0 \tag{16}$$

An unexpected decrease in emissions, for example, triggers a price reduction in period one. This in turn triggers a combination of an emission increase in period one and an increase in banking and hedging from period one to 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, market participants cannot bank allowances for use in later periods:

$$Q_2^{surplus} + Q_1^h + Q_1^s = 0 \tag{17}$$

To solve the model we consider two cases: equilibrium with and without demand from speculative investors.

Equilibrium in case of no speculative demand

In case one, speculators expect that the carbon price will increase at a rate below their return requirements, $\delta_{CO2}^{e} < \delta_{CO2}^{s}$, and thus speculative demand is zero. Solving the market equilibrium for the price in period one yields:

$$p_1^{CO2} = \frac{-\theta_1 + \gamma\left(C\, i_{CO2}^{c} + G\, i_{CO2}^{g}\right)}{\beta_1 + \frac{[i_{CO2}^{c}]^2 + \left[i_{CO2}^{g}\right]^2}{2\,\alpha}} \tag{18}$$
$$+ \frac{\left(-\theta_2\,\beta_1 - (\theta_1 + \theta_2)\frac{[i_{CO2}^{c}]^2 + \left[i_{CO2}^{g}\right]^2}{2\,\alpha} - \gamma\,\beta_1\left(C\, i_{CO2}^{c} + G\, i_{CO2}^{g}\right)\right)\frac{[i_{CO2}^{c}]^2 + \left[i_{CO2}^{g}\right]^2}{2\,\alpha(1 + \delta_{CO2}^{m})^n}}{\left(\left(\beta_1 + \frac{[i_{CO2}^{c}]^2 + \left[i_{CO2}^{g}\right]^2}{2\,\alpha}\right)\left(\beta_2 + \frac{[i_{CO2}^{c}]^2 + \left[i_{CO2}^{g}\right]^2}{2\,\alpha(1 + \delta_{CO2}^{m})^n}\right) - \frac{\left([i_{CO2}^{c}]^2 + \left[i_{CO2}^{g}\right]^2\right)^2}{4\alpha^2(1 + \delta_{CO2}^{m})^n}\right)\left(\beta_1 + \frac{[i_{CO2}^{c}]^2 + \left[i_{CO2}^{g}\right]^2}{2\,\alpha}\right)}$$

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

$$E(p_2^{CO2})= \frac{-\theta_2\,\beta_1 - (\theta_1+\theta_2)\frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\,\alpha} - \gamma\,\beta_1\left(C\,i_{CO2}^c + G\,i_{CO2}^g\right)}{\left(\beta_1 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\,\alpha}\right)\left(\beta_2 + \frac{[i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2}{2\,\alpha(1+\delta_{CO2}^m)^n}\right) - \frac{\left([i_{CO2}^c]^2 + \left[i_{CO2}^g\right]^2\right)^2}{4\,\alpha^2(1+\delta_{CO2}^m)^n}} \tag{19}$$

In equilibrium, carbon prices decrease with increasing surplus parameters θ_1 and θ_2 and with increasing emission responsiveness parameters β_1 and two β_2. If the hedging volume by power firms increases in period one and adds to the surplus in period two, the price in period one increases and decreases in period two.

Equilibrium in case of speculative demand

In case two, speculators expect that the carbon price will increase at a rate above or equal to their return requirements, $\delta_{CO2}^e \geq \delta_{CO2}^s$. To simplify the calculations we assume $\varphi \rightarrow \infty$. Combining $\delta_{CO2}^e = \delta_{CO2}^s$ with the allowance balance across the periods

$$\theta_1 + \beta_1\,p_1^{CO2} + \theta_2 + \beta_2\,E(p_2^{CO2}) = 0 \tag{20}$$

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

$$p_1^{CO2^*} = \frac{-(\theta_1+\theta_2)}{\beta_1 + \beta_2(1+\delta_{CO2}^s)^n} \tag{21}$$

$$E(p_2^{CO2})^* = \frac{-(\theta_1+\theta_2)(1+\delta_{CO2}^s)^n}{\beta_1 + \beta_2(1+\delta_{CO2}^s)^n} \tag{22}$$

The higher that the required rate of return by speculators δ_{CO2}^s is, the lower that prices are in equilibrium.

3.2 Parameterisation of CO_2 emitters, hedgers and speculators

To calibrate the model, we use the parameters in Table 4. We calibrate the surplus parameters θ_1 and θ_2 and the emission responsiveness parameters β_1 and β_2, so that the surplus $Q_1^{surplus}$matches the CO_2 hedging volume Q_1^h of 1.4 billion tonnes of CO_2 and banking is pursued at modest discount rates of 5 percent. This corresponds to the implied discount rates from EU ETS impact assessments. These assumed a price of 30 Euro for 2020 at the beginning of the second trading period. Given a 2008 price of about 20 Euro, this implies an annual discount rate of more than 3 percent (DECC, 2009; EU, 2008). Banking at discount rates of 3 – 5 percent is also assumed in economic models to evaluate carbon markets (Bosetti et al., 2009; Ellerman and Montero, 2007).

The hedging flexibility by power firms in the four-period model ranges from 1.1 to 1.7 billion tonnes of CO_2. This holds if firms apply discount rates of 0 - 10 percent to price expectations and a given α that reflects firm's sensitivity to deviations from the hedging schedule. To translate the same range of flexibility into the simplified two-period framework, we reduce the parameter α to 0.00001 Euro/GWh. The hedging schedule γ of 150 percent corresponds to the 84 percent of power hedged one year in advance, 46 percent two years in advance and 20 percent three years in advance.

In the EU ETS, the third trading period covers eight years from 2013 to 2020. Therefore, we consider price equilibriums for the case that one period in our two-period model corresponds to eight years $n = 8$. Moreover, the emissions' responsiveness to prices is assumed to increase in period two, $\beta_2 > \beta_1$, as in the long term firms can adapt to carbon prices through investment choices.

Table 1: Parameter assumptions of demand-supply model

Parameter	Unit	Value
θ_1	Billion t CO_2	1.1
θ_2	Billion t CO_2	-2.5
β_1	Billion tCO_2^2/ Euro	0.020
β_2	Billion tCO_2^2/ Euro	0.050
γ	Percent	150
δ_{CO2}^{m}	Percent	5
n	Years	8
α	Euro /GWh	0. 00001
δ_{CO2}^{s}	Percent	15

3.3 Quantification of carbon price impact

The two-period model of CO_2 hedgers, emitters and speculators can demonstrate how current carbon prices relate to current demand and supply of allowances, future scarcity, and discount rates applied to expected carbon prices.

Figure 4 depicts price equilibriums for different surplus levels in period one. The prices in market equilibrium decrease with the surplus of CO_2 allowances. As the surplus in period one increases, the discrepancy between today's price and price expectations widens and the discount rates that market participants apply to price expectations increase. This discrepancy amplifies as one period corresponds to eight years and therefore discounting multiplies by eight. Providing the cumulative surplus is below the 1.7 billion tonnes of CO_2 that can be absorbed by hedgers (black lines), discount rates below 10 percent are obtained. For surpluses above this level, the current price decreases and discount rates increase to 15 percent, so that speculative investors enter the market and stabilise the discount rate that applies with further increases of the surplus in period one at this level (slope change in black lines). This change in discount rates applied to price expectations contrasts with economic models that assume unlimited availability of banking at discount rates of 5 percent (grey lines).

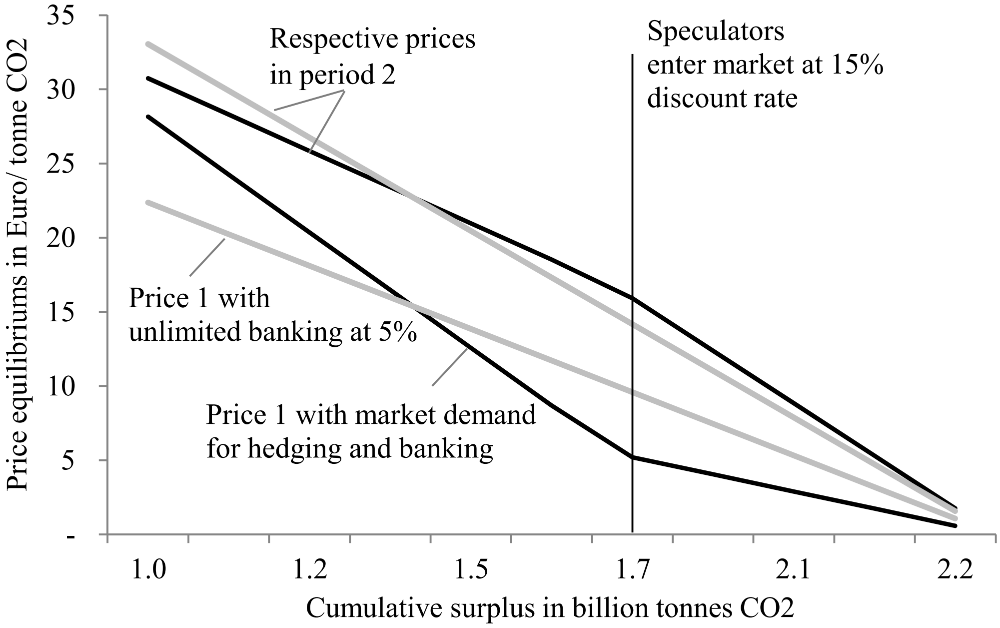

Figure 1: Price equilibriums for different surplus levels

To illustrate how the model can help explain recent price developments in the EU ETS, we apply it to a situation where the surplus exceeds CO_2 hedging by power firms, and speculative investment in allowances is required to balance the market. In the EU ETS, the cumulative surplus is estimated to be 2.2 billion tonnes of CO_2 in 2012 (Neuhoff et al., 2012). In order to return to a situation where banking can be pursued at discount rates in the order of 5 percent, the surplus needs to be reduced.

Figure 5 shows carbon price developments for the market equilibrium with speculators, and two policy options for reducing the surplus, backloading and a permanent set-aside. In the market equilibrium with speculators, the surplus amounts to 2.2 billion tonnes of CO_2. Since the surplus exceeds hedging demand by power firms, the remaining surplus allowances are banked as speculative investment. Therefore, the current price decreases, so that speculators can expect to earn annual rates of return of 15 percent.

Backloading 0.9 billion tonnes of CO_2 from period one to period two, as proposed by the European Commission (2012a), reduces the volume of allowances that needs to be banked in period one. This means that surplus allowances can be absorbed by hedgers and prices in period one increase slightly. Since the retained allowances are released in period two, price expectations decrease.

Setting aside 0.9 billion tonnes of CO_2 in period one also reduces the surplus so that it can be absorbed by hedgers. Since allowances are permanently retained, prices increase in period one and two. This allows banking for hedging purposes at low discount rates.

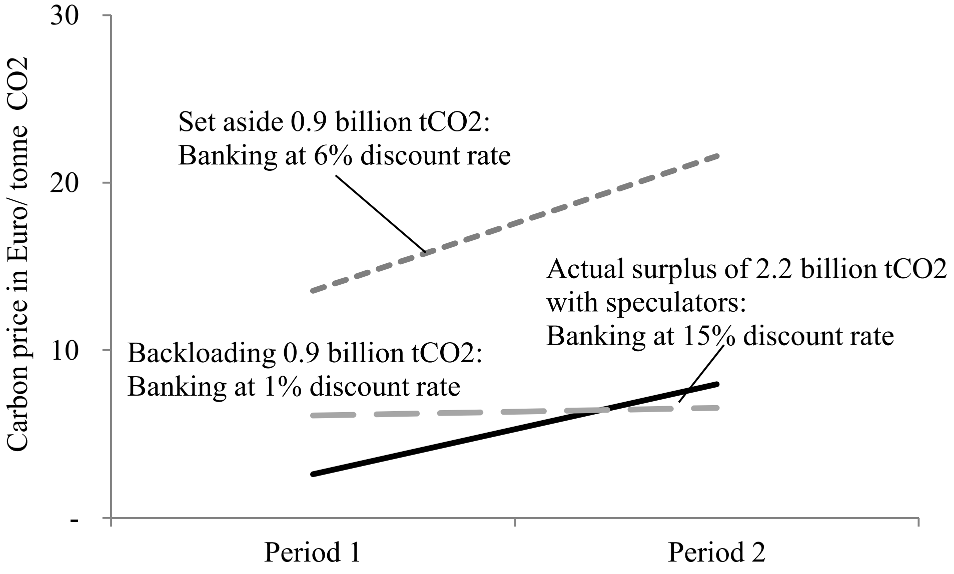

Figure 2: Impact of policy options on discounting of price expectations

These calculations are subject to a degree of uncertainty owing to the limited data available. The industry sector has not been considered. However, industry may have also banked a few million allowances. Between 2008 and 2010 industrial emitters received 569 million allowances gratis beyond their need to cover annual emissions.

Furthermore, our hedging estimate of 1.4 billion tonnes CO_2 relies on hedging strategies and power production data from 2010 annual reports and a survey of power hedging carried out by Eurelectric. Several factors may impact the hedging level. First, power production has decreased by 3 percent since 2010. Second, changes in the power market and the forward contracting have an impact on CO_2 hedging volumes. For example, with shares in renewable energy on the increase, the need for forward contracting for coal and carbon emission allowances will fall.

Keeping these caveats in mind, we present a simple analytic framework to demonstrate the EU ETS price dynamics accounting for different types of actors who bank EU ETS surplus allowances.

4. Conclusion

One benefit of banking, as highlighted in the literature, is that market participants can smooth emission mitigation costs over time. This means that if the surplus is high and prices are low, they can bank allowances for future use when they expect prices to be higher. Banking can thereby help to stabilise carbon prices and contribute to inter-temporal efficiency.

We differentiate two types of banking, i.e. hedging and speculation. Market participants can bank carbon emission allowances to meet future compliance obligations. As allowances do not have any storage cost, banks can buy allowances at the spot market and offer forward contracts up to 3 - 4 years ahead of delivery to hedging firms at a price that covers their opportunity cost of capital. This carbon arbitrage is reflected in forward contract prices being traded generally at 3 - 5 percent discount above spot prices in the second trading period. In a situation where surplus allowances exceed hedging needs, allowances are banked as a speculative investment. Speculative investors, however, require higher annual rates of return to cover the risks associated with future carbon price developments. This implies that long term carbon price expectations are highly discounted and thus can depress current prices.

To illustrate this effect, we model the different types of banking in a simple two period demand and supply model. Two main factors that determine the volume of CO_2 hedging by European power firms are identified, recording information from 13 interviews: 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 when forward prices deviate significantly from expectations determined 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 volume in a range of 1.1 to 1.7 billion tonnes by the end of 2012, for discount rates of 0 - 10 percent. We then model the interactions between CO_2 hedging by power firms, CO_2 banking by speculative investors and carbon price dependent emission levels in a two-period framework. As the surplus increases, the discrepancy between forward prices and price expectations widens.

Further analysis is required to determine the type of reforms needed to guarantee that the surplus stays within limits where banking can be pursued at modest discount rates. In particular, uncertainties remain around the variance of actual emissions, the responsiveness of emissions to prices and the overall impact of the forward contracting market if CO_2 hedging opportunities change. One way of reducing exposure to external shocks, such as the financial crisis, would be to determine the emission cap for allowances not for twelve years ahead, as was done in 2008 for the period up to 2020, but rather for shorter time frames. For example, Australia allows an adjustment of the cap every five years and the Regional Greenhouse Gas Initiative in the US is able to do so every three years. Other options to increase flexibility on the supply side are the market stability reserve as proposed by the European Commission that withholds allowances beyond the hedging corridor from the market and thus could in principle substitute for the role of speculative long-term investors.

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