Supply-Side Perspective for Carbon Pricing

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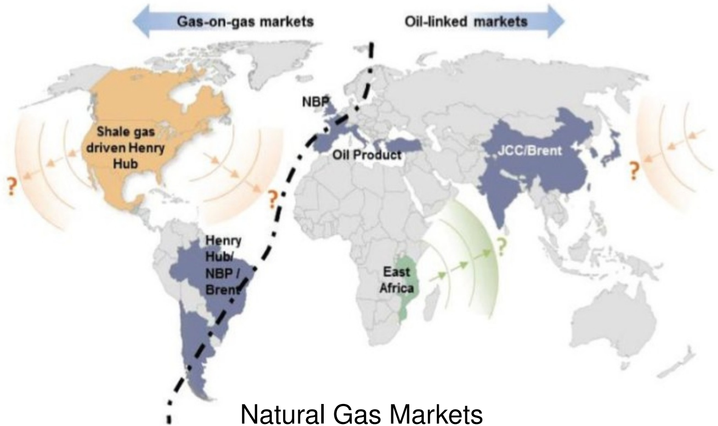
Outline

Background

- Commodity transaction including energy basically starts with long-term contracts from supply-side perspective of commodities.
- The supply sides certainly attempt to recover the production costs in the early stage of commodity trading.
- It also fits well to the demand side preference of its commodity purchase with a stable constant price in the absence of the liquid spot markets even if the constant price is more or less expensive for consumers.
- Natural gas trading is known to introduce long-term contracts between supply and demand sides, resulting in crude oil-linked pricing (see, e.g., Stern (2007)).
- When the liquidity of energy trading fully increases, as the next step of long-term contracts energy tends to be evaluated in the market using a supply and demand-based pricing.

Background (cont'd)

Regional long-term contract pricing structure



Natural Gas Markets
(https://magnuscmdblog.wordpress.com/2016/06/27/is-asia-becoming-the-new-el-dorado-of-natural-gas/)

The US natural gas prices are determined by the supply and demand.

Background (cont'd)

- In contrast to energy commodities, emissions politically and artificially start with market-based trade whose prices are determined by the supply and demand for emissions as observed in the EU-ETS.
- Carbon assets can be transacted in a supply and demand-based market without high liquidity of carbon trading, which is different from market development processes of energy commodities.
- This can be a reason why carbon markets do not work well, resulting in low prices less than 10 EUR/tonne, i.e., a recent low price issue in carbon markets.

Background (cont'd)

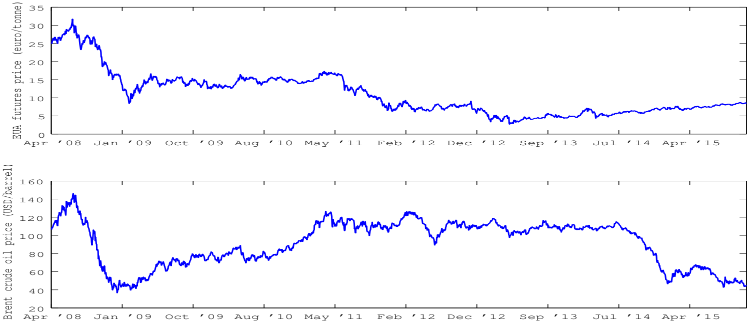


Figure 1: EUA futures and Brent crude oil prices

- Low carbon prices are quite problematic for accelerating the developments of carbon reduction technologies.
- Low price carbon assets are favored by carbon reduction obligators other than the introduction of new carbon emission reduction technologies with high marginal abatement costs.

Background (cont'd)

- We revisit carbon pricing to solve a recent low carbon price issue.
- It is well known that crude oil markets represent one of the basic fundamentals of economy.
- It implies that high crude oil prices can be driven by strong economy, resulting in large carbon emissions and high carbon prices.
- In a first order approximation it is assumed that carbon prices can positively be affected by crude oil prices.

Background (cont'd)

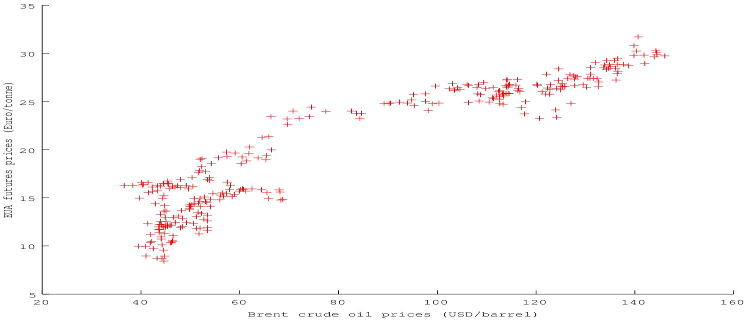


Figure 2: Scatter plots between Brent crude oil and EUA futures prices (April, 2008 to June, 2009)

- In order to examine the relation between carbon and energy, we show scatter plots between Brent crude oil and EUA futures prices in Figure 2.
- It seems an upward sloping nonlinear relation between Brent crude oil and EUA futures prices, resulting in the positive support of crude oil-linked pricing of carbon products.

Literature Survey

- In the last decade, the development of carbon markets has attracted great academic interest.
- Fehr and Hinz (2006) propose an equilibrium price model for EUA prices taking into account fuel switching between natural gas and coal fired power plants. and Trück (2009) employ an AR-GARCH Markov switching price return model to capture regime changes between different phases of the EU-ETS and heteroskedasticty.
- Daskalakis, Psychoyios, and Markellos (2009) compare existing popular diffusion and jump diffusion models, with the results in favor of the Geometric Brownian motion with jumps to fit historical EUA spot prices, unlike the mean-reverting processes often used for commodity price modeling.
- Seifert, Uhrig-Homburg, and Wagner (2008) propose a stochastic model of CO_2 prices which do not have any seasonal pattern, as often observed in commodity markets.

Literature Survey (cont'd)

- Paolella and Taschini (2008) also propose mixed normal and mixed stable GARCH models to capture the heavy tails and volatility clustering in the U.S. SO_2 permits and EUA price returns, which are not modeled using any mean-reversion and seasonality.
- Uhrig-Homburg and Wagner (2009) examine the relation between carbon spot and futures prices traded on the Powernext and the European Climate Exchange.
- Trück, Härdle, and Weron (2015) conduct empirical analyses of EUA convenience yields using the spot and futures prices traded on the EEX and presenting a convenience yield model based on the spot prices and volatilities.
- Kanamura (2009a) also investigate the characteristics of carbon asset prices, resulting in the possibility of classifying carbon assets into non commodity assets.
- Gorenflo (2013) analyzes the pricing and lead–lag relation between EUA spot and futures prices.

Literature Survey (cont'd)

- Other papers for carbon markets focus on price determination in carbon markets.
- The relations between EUA futures prices and macroeconomic factors, including stock and bond market variables, are found in Chevallier (2009).
- Fezzi and Bunn (2009) show that carbon prices accompanied by natural gas prices drive electricity prices in the UK.
- Hintermann (2010) investigates whether marginal abatement costs explain EUA prices in the first phase of the EU-ETS or not.
- Bredin and Muckley (2011) examine the impacts of economic growth, energy prices, and weather on EUA futures prices.
- Chevallier (2011a) suggests that yearly compliance events and growing uncertainties in post-Kyoto international agreements may explain the instability in carbon price volatilities.
- Chevallier (2011b) develops a carbon pricing model with two basic EUA price drivers of economic activity and energy prices.

Literature Survey (cont'd)

- Gronwald, Ketterer, and Trück (2011) find a strong dependence between EUA futures price returns and those of other financial assets and commodities during the period of the financial crisis.
- Aatola, Ollikainen, and Toppinen (2013) discover a strong relation between EUA prices and energy prices, including German electricity prices and gas and coal prices.
- Kanamura (2016) theoretically and empirically examines the role of carbon swap trading and energy prices in volatilities and price correlations between the EU and Kyoto Protocol emissions trading schemes.
- While these studies keep eyes on carbon price models and the empirical analyses of carbon markets, they do not seem to pay attention to direct modeling of carbon prices using the linkage of carbon prices to crude oil prices.

The objectives

- This paper theoretically and empirically revisits carbon pricing from the supply-side perspective for carbon assets to solve a recent low price issue, which may delay the development of emission reduction technologies in the sense of marginal abatement costs.

The results

(1) We propose a carbon pricing model linked to crude oil prices, which is employed in supply-side driven pricing of long-term contracts for energy trading in the early stage.

(2) It is shown that since the model is designed to hold carbon prices between certain lower and upper boundaries using S-shaped carbon price linkage to crude oil prices, it can be useful to overcome a recent low carbon price issue.

(3) It is shown that the model can alleviate the difficulties of carbon derivative pricing in selecting market price of risk.

The results (cont'd)

(4) Empirical studies using EUA and Brent crude oil futures prices estimate the parameters of the Brent crude oil-linked EUA price model.

(5) The results suggest that simulated EUA prices from the model be kept relatively higher than historical EUA prices.

(6) To show usefulness of crude oil-linked carbon pricing, we also give a numerical example of European carbon option pricing based on the Brent crude oil-linked EUA price model by using Crank-Nicolson finite difference method.

(7) We discuss the relation between crude oil-linked carbon pricing and emission reduction risk.

A crude oil-linked carbon price model

- Energy transaction including natural gas is conducted using long-term contracts in the early stage where prices are linked to crude oil prices from the supply-side perspective for energy.
- Japanese liquefied natural gas (LNG) is priced using the linkage to crude oil prices.
- After the liquidity of energy transaction increases, the pricing mechanism is transferred from the oil linked pricing to market-based pricing where the supply and demand for energy determine the prices, e.g., the US natural gas market.
- On the other hand, while carbon assets are considered as energy related assets, the pricing employs market-based pricing from the beginning where the supply and demand for emissions determine the prices, not based on energy-linked pricing.
- We consider that the development process of carbon markets is different from the other energy markets in the sense of pricing mechanism.

A crude oil-linked carbon price model (cont'd)

- When energy prices increase, the world economy is likely to grow rapidly as observed during commodity boom period from 2005 to 2007.
- It will increase the output of emissions in the world, resulting in high appreciation of carbon assets.
- Carbon prices may also have positive linkage to energy prices.
- Following this idea, we propose a carbon pricing model which is linked to crude oil prices.
- Crude oil price (P_t) model is given by

$$P_t = \left(1 + a\frac{V_t}{c}\right)^{\frac{1}{a}}, \tag{1}$$

$$dV_t = \mu_V dt + \sigma_V dw_t. \tag{2}$$

- The inverse Box-Cox transformation function in Eq. (1) and the stochastic process in Eq. (2) represent a crude oil supply curve and the demand fluctuation of V_t, respectively.

A crude oil-linked carbon price model (cont'd)

- By using Ito's lemma, we have crude oil price model:

$$\frac{dP_t}{P_t} = \mu_P dt + \sigma_P dw_t, \tag{3}$$

$$\mu_P = \frac{\mu_V}{\sigma_V}\sigma_P + \frac{1}{2}(1-a)\sigma_P^2, \tag{4}$$

$$\sigma_P = \frac{\sigma_V}{c} P_t^{-a}. \tag{5}$$

- Carbon price is defined using S-shaped logit model which has price cap (A) and floor (B).

$$C_t = \frac{Ae^{\alpha+\beta P_t} + B}{1 + e^{\alpha+\beta P_t}} \tag{6}$$

- This is referred to as "a crude oil-linked carbon price model."

Characteristics of a crude oil-linked carbon price model

- Since the model holds carbon prices between certain lower and upper boundaries, it can accelerate to develop emission reduction technologies in the sense of marginal abatement costs by resolving a recent low carbon price issue.
- Note that

$$\frac{\partial C_t}{\partial P_t} = \frac{(A - B)\beta e^{\alpha+\beta P_t}}{(1 + e^{\alpha+\beta P_t})^2}. \tag{7}$$

- Taking into account $A - B > 0$ by definition, if $\beta > 0$, then carbon price C_t is an increasing function of crude oil price P_t.

Derivative pricing on a crude oil-linked carbon price model

- It is hard to price carbon derivatives due to the illiquidity of carbon derivative markets, resulting in the incomplete market pricing and difficulties in selecting carbon market price of risk.
- As the advantage of the crude oil-linked carbon price model, the market price of risk for carbon derivatives can be selected as crude oil market price of risk, which can be more reliable than carbon market price of risk in the sense of market liquidity.
- The European call option price (f_t) on carbon prices from crude oil prices is calculated using the following equation.

$$f_t = E_t\left[\frac{\Lambda_T}{\Lambda_t}(C(P_T) - K)^+\right] \tag{8}$$

where $C(P_T)$ is carbon price at time T using crude oil price (P_T), Λ_t is a stochastic discount factor at time t, and K is the strike.

Derivative pricing on a crude oil-linked carbon price model (cont'd)

- We assume the stochastic discount factor is given by

$$\frac{d\Lambda_t}{\Lambda_t} = -rdt - \phi_P dw_t. \tag{9}$$

- Note that $\phi_P = \frac{\mu_P - r}{\sigma_P}$ is crude oil market price of risk.
- By using Ito's Lemma, we have the partial differential equation for the option prices:

$$\frac{\partial f_t}{\partial t} + rP_t \frac{\partial f_t}{\partial P_t} + \frac{1}{2}\sigma_P^2 P_t^2 \frac{\partial^2 f_t}{\partial P_t^2} - rf_t = 0, \tag{10}$$

$$f_T = (C(P_T) - K)^+. \tag{11}$$

- By solving the PDE from time T to t numerically, we can obtain the call option price at time t.
- It was shown that the crude oil-linked carbon pricing model can alleviate the difficulties of carbon derivative pricing in the sense of the selection of the market price of risk.

Data

- We use Brent crude oil and EUA futures price data obtained from the website of Quandl.
- It covers from April 8, 2008 to June 5, 2009 (300 sample size).

	Brent	EUA
Mean	81.14	20.14
Maximum	146.08	31.71
Minimum	36.61	8.43
Std. Dev.	35.52	6.44
Skewness	0.37	-0.05
Kurtosis	1.48	1.50

Table1: Basic Statistics

- The basic statistics are reported in Table 1.
- The skewness of Brent crude oil prices is positive while the skewness of EUA prices is negative, resulting in right-skewed and left-skewed distributions, respectively.

The model parameter estimation

- Assuming $A = 31.71$ and $B = 8.43$ which are maximum and minimum of the sample carbon price data, respectively in Table 1 we consider the following nonlinear regression model for Eq. (6), i.e., a modified logit regression model (u_t is an error term).

$$C_t = \frac{Ae^{\alpha+\beta P_t} + B}{1 + e^{\alpha+\beta P_t}} + u_t \tag{12}$$

- The estimation results of the non-linear regression model for Eq. (6) are reported in Table 2 based on non-linear least squares.

	α	β
Parameters	-2.733	3.492E-02
Std. Error	0.077	9.787E-04
Log likelihood	290.695	
AIC	-577.389	
SIC	-569.982	

Table 2: Modified logit regression model parameter estimation for EUA and Brent crude oil prices

- The parameters are statistically significant from the SEs.
- Since $\beta > 0$, carbon prices increase in line with crude oil prices.

The model parameter estimation (cont'd)

- We draw the model estimation results on the scatter plots between Brent crude oil and EUA prices in Figure 3, which suggests that the model fit well to the historical scatter plots.

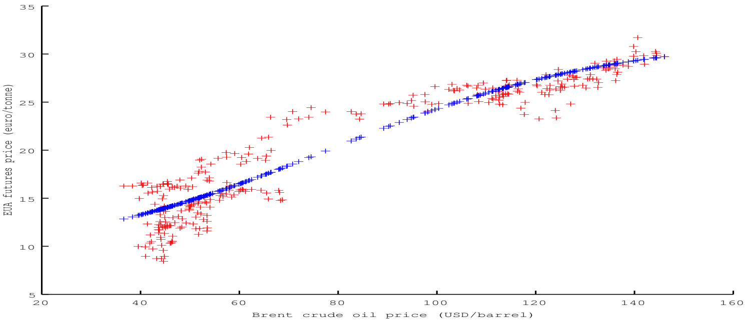


Figure 3: Scatter plots between Brent crude oil and historical (red plots) & estimated (blue plots) EUA futures prices (April, 2008 to June, 2009)

The model parameter estimation (cont'd)

- We estimate crude oil price model in Eqs. (3) to (5) discretized:

$$\log P_{t+1} - \log P_t = (k\sigma_P - \frac{1}{2}a\sigma_P^2)\Delta t + \sigma_P \epsilon_t, \quad (13)$$

$$\sigma_P = \bar{\sigma}_P P_t^{-a}. \quad (14)$$

Note that $k = \frac{\mu_V}{\sigma_V}$, $\bar{\sigma}_P = \frac{\sigma_V}{c}$, $\Delta t = \frac{1}{252}$, and $\epsilon_t \sim \mathrm{N}(0, \frac{1}{252})$.

- The results using LME are reported in Table 3.

Parameters	k	a	$\bar{\sigma}_P$
Estimates	-0.682	0.606	7.450
Standard errors	0.865	0.009	0.295
Log likelihood	613		
AIC	-1,220		
SIC	-1,226		

Table 3: Brent crude oil price model parameter estimation

- Inverse Box-Cox param. for the supply curve (a) and volatility param. for crude oil price ($\bar{\sigma}_P$) are positive and stat. significant.
- The positive a suggests leverage effect for crude oil prices.

Out of sample data and crude oil-linked carbon price simulation

- We simulate EUA prices from crude oil prices by using the Brent crude oil-linked EUA price model.
- As out of sample data, we employ the data covering from June 8, 2009 to November 23, 2015.
- The simulation results accompanied by out of sample carbon price data are shown in Figure 4.

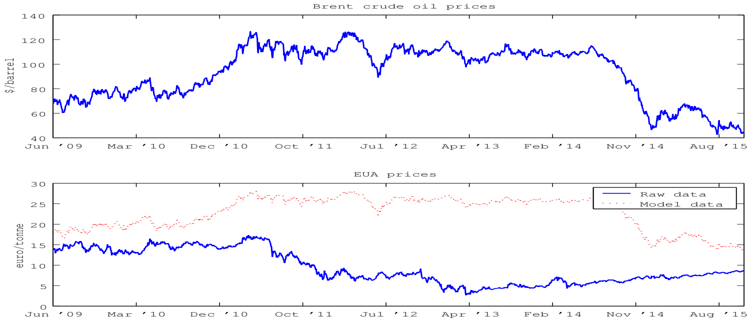


Figure 4: Brent crude oil prices and EUA prices (historical data & model simulated data)

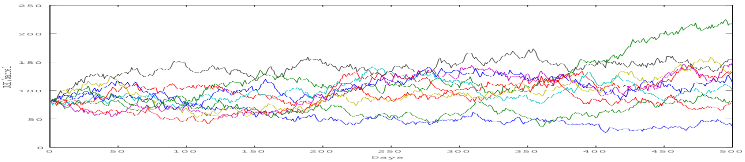
Out of sample data and the model simulation (cont'd)

- It suggests that EUA prices simulated from the Brent crude oil-linked EUA price model are kept relatively higher than historical prices.
- The characteristics of simulated EUA prices are helpful to accelerate the developments of emission reduction technologies because high carbon prices allow emission reduction technologies with expensive marginal abatement costs.
- It may imply that EUA must be priced using a crude oil-linked carbon price model, not employing a premature market-based or supply and demand-based carbon price model.

Out of sample data and the model simulation (cont'd)

- We finally show ten sample paths simulated by both Brent crude oil price model and the Brent crude oil-linked EUA price model in Eqs. (3) and (6), respectively.
- The results are reported in Figure 5.

Panel A Brent crude oil price



Panel B EUA price

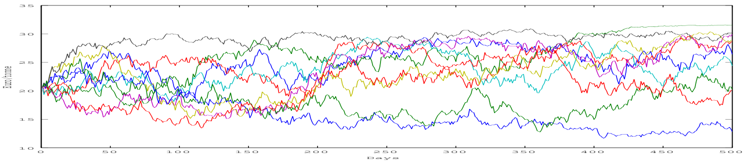


Figure 5: Brent crude oil and EUA price simulations

Carbon call option pricing

- In order to show usefulness of crude oil-linked carbon pricing, we give a numerical example of European carbon option pricing based on the Brent crude oil-linked EUA price model by using Crank-Nicolson finite difference method.
- Partial differential equation in Eq. (10) is solved backwards in time from 0.25 year (3 months) to 0 by setting the terminal condition in Eq. (11). Note that we assume $r = 0.05$ per annum.
- The results are reported in Figure 5 where the strike is 20 EUR/tonne for EUA price, which is close to the sample average of Table 1.

Carbon call option pricing (cont'd)

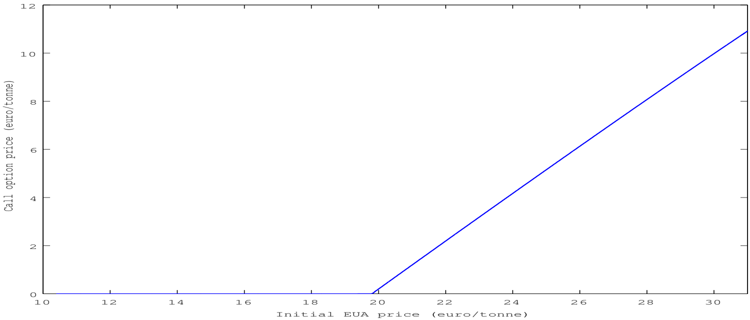


Figure 5: European carbon option price based on the Brant crude oil-linked EUA price model

- The results empirically suggest that the model can alleviate the difficulties of carbon derivative pricing in the sense of selecting the market price of risk by showing that the call option prices are numerically obtained based on the crude oil-linked carbon pricing.

Discussions

- When we look at the track records of the relations between crude oil and carbon prices as in Figure 3, carbon prices move in line with crude oil prices.
- This model also makes sense in the relations between world economy development and carbon emission outputs.
- If energy consumptions, in particular crude oil consumptions, increase, not only will crude oil price rise due to the supply and demand, but carbon prices will also rise due to the increase in energy consumptions.
- It implies that energy consumers will economically have burdens from the rise in carbon prices as well as those from the rise in energy prices.
- Energy consumers have strong incentives not only to reduce energy use so as to alleviate both impacts of energy and carbon prices on their businesses but also to introduce new emission reduction technologies with lower MACs than carbon assets.

Discussions (cont'd)

- In contrast if energy consumption level is low, then emission itself becomes small.
- We do not need any new emission reduction technologies.
- In summary, when emissions increase, the introduction of a crude oil-linked carbon price model to carbon markets forces energy consumers to reduce the emissions.
- In contrast, when emissions decrease, the introduction of the model makes energy consumers release their burdens from emission reductions.
- In this sense, the introduction of a crude oil-linked carbon price model to carbon markets may offer a natural hedge of emission reduction risk for energy consumers.

Conclusions

(1) We proposed a carbon pricing model linked to crude oil prices, which is employed in supply-side driven pricing of long-term contracts for energy trading in the early stage.

(2) It was shown that since the model is designed to hold carbon prices between certain lower and upper boundaries using S-shaped carbon price linkage to crude oil prices, it can be useful to overcome a recent low carbon price issue.

(3) It was shown that the model can alleviate the difficulties of carbon derivative pricing in selecting market price of risk.

Conclusions (cont'd)

(4) Empirical studies using EUA and Brent crude oil futures prices estimated the parameters of the Brent crude oil-linked EUA price model.

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(7) We discussed the relation between crude oil-linked carbon pricing and emission reduction risk and showed that the introduction of a crude oil-linked carbon price model to carbon markets may offer a natural hedge of emission reduction risk for energy consumers.

Thank you

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