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Gas Storage Pricing and Hedging

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THE ROLE OF STORAGE IN NATURAL-GAS MARKETS

Storage plays a vital role in competitive natural-gas markets, because the average variability in the consumption of natural gas is much greater than the average variability in production. Historically, natural-gas storage has been used for two key functions. First, it provides local distribution companies with adequate supply during periods of heavy demand by supplementing pipeline capacity and serving as backup supply in case of an interruption in wellhead production. Second, storage enables greater system efficiency: instead of satisfying winter demand by adding new production facilities, the industry can maintain production at a much more constant level throughout the year. Finally, during periods of significant changes in supply or demand, storage ensures pipeline integrity is maintained.

As part of the liberalisation process in many countries the natural-gas storage service has been unbundled from the sales and transportation services, meaning that storage is increasingly offered as a distinct, separately charged service. In combination with the development of active spot and futures markets, it becomes possible to adjust trading decisions to price conditions. In other words, buyers and sellers of natural gas have the possibility to use storage capacity to take advantage of the volatility in prices.

There are four main operating characteristics of a gas storage: cushion gas capacity, working gas capacity, withdrawal rate (deliverability) and injection rate.

The base gas, or cushion, is the amount of gas required to maintain adequate reservoir pressure and is generally never removed; the filling of the cushion gas may be the largest part of the investment in a new storage, but it is not relevant for the pricing and optimisation afterwards, because it can be considered a sunk cost.

The working gas capacity is the amount of gas that is available to produce and sell, and hence the relevant capacity for day-to-day usage.

Deliverability refers to the rate at which the asset can withdraw gas from the storage into the gas pipeline system. Deliverability tends to be highest when the reservoir is closest to its maximum capacity and lowest when the reservoir is nearly empty. For tradable storage products (standard bundled units), the withdrawal rate is often kept constant, to simplify trading decisions.

The same holds for the injection rate, which refers to the rate at which natural gas can be pumped into storage for later use. In contrast to the deliverability, the injection rate of a physical storage is at its lowest when the reservoir is at maximum capacity and is at its highest when the reservoir is empty.

Optimising storage trading and operational decisions is important for owners of physical storage assets, because it helps them maximise storage value. At the same time, owners of storage often sell (part of) their facility to the market, either as physical contracts or as purely financial contracts. An alternative to physical storage is the so-called virtual storage. The virtual storage provider does not have to keep physical storage capacity. The seller offers a storage service that is supported through swing gas,[1] spot market deals, some physical storage and other trading instruments. This type of service is increasingly being used in the matured gas markets in the US, the UK and some continental European gas markets. In the remainder of this chapter the gas storage may either mean the physical service or the virtual (financial) product.

The chapter is organised as follows. In the next section, we present market price trends, then explain the intrinsic and rolling intrinsic valuation and trading approaches. Actually, gas market prices in Europe and North America had moved in a disadvantageous direction for storage market players between 2009 and 2015: seasonal spreads and market price volatility had gone down, reducing the value of gas storage. As a result, it has become even more important for storage traders to optimise their trading strategies.

In the section following, we explain how this can be achieved using the real-option approach. With this approach, today's trading decisions take into account the anticipated dynamics in gas market prices. This leads to more optimal spot trading decisions, whereas the price risks can be mitigated through delta hedging.

Finally, we discuss the calibration of the most relevant market price parameters, in particular spot price volatility and mean-reversion. The conclusion follows.

PANEL 15.1 ROUGH GAS STORAGE PRODUCTS

Centrica Storage operates the largest UK storage asset, called Rough. Rough is a depleted gas production field a few miles off the east coast of Yorkshire, in the North Sea. It began producing gas in 1975 and was converted into a storage facility in 1985. According to National Grid, Rough working volume alone makes up 72% of the UK's existing gas storage capacity. Going through a complete cycle of injection and withdrawal takes around 250 days, so it falls into the category of seasonal storage facilities. Still, the deliverability is high enough to meet approximately 10% of the UK's winter peak day demand.

Centrica Storage offers different storage products to the market, called S Store, C Store and V Store. All storage products are for a particular storage year, starting either on April 1 or May 1. The S Store product is a physical storage product. The standard bundled unit (SBU) consists of 66.6 kWh of working volume ("space"), 1 kWh of withdrawal per day and 0.35 kWh injection per day, delivered at the Easington connection point. The day-ahead product allows the users of the service to nominate injections and withdrawals up to two hours before the next gas day begins. The within-day product allows nomination per hour until shortly before the hour starts, and is therefore slightly more expensive. The withdrawal rates are fixed (1 kWh per day), whereas the injection rates may vary over time, depending on the aggregate fullness of the facility, and are published on a daily basis by Centrica Storage.

The C Store product is essentially the same product, but with the advantage that no entry capacity to the National Transport System at Easington needs to be purchased. Gas nominated for withdrawal during the Winter period (October 1 to March 31) is delivered directly to the UK's NBP market. V Store is a virtual product offering even greater flexibility than C Store: the injection rates are firm and fixed and any nominated injections and withdrawals are directly brought to the NBP.

The users of the services may trade injection and withdrawal rates among each other, because these are transferable. In addition to these three storage products, Rough users may purchase various types of interruptible capacities, which become available when other Rough clients do not use their capacities according to the “use it or lose it” principle.

Storage SBUs may be bought on a fixed-price basis or on an indexed-price basis. The index is a combination of forward price assessments from Heren and Argus, as well as futures prices listed on the ICE exchange. It equals the difference between the forward “winter” price (first quarter of the year) minus the forward “summer” price of the previous year. For example, the storage product may be priced at a multiple of 1.3 times the average index price over a predefined price period.

PANEL 15.2 BERGERMEER GAS STORAGE PRODUCTS

TAQA, a company of the United Arab Emirates, began the full commercial operations of the Bergermeer gas storage facility in 2015. Bergermeer is located on the northwest coast of the Netherlands, near the town of Alkmaar. Bergermeer is connected to the Dutch TTF market, which is the most liquid natural-gas trading market together with the NBP market in the UK. The physical characteristics of Bergermeer are similar to those of Rough, with an even larger working volume, slightly faster injectability and slightly slower deliverability.

TAQA has tried to incorporate the lessons learned from other storage providers and facilitate trading of storage products as much as possible. For example, the service is delivered directly at the TTF, with no need to purchase entry or exit capacity by the individual users. Furthermore, there is a standard index pricing of SBUs against the differential between Q1 (“winter”) and Q2+Q3 (“summer”) futures prices on the ICE exchange. The index is calculated over a six-month period prior to the start of the storage year. Market players may bid for SBUs at a multiplier. For example, in periodic auctions, capacity is sold for one, two or three storage years, with multipliers of about 1.15.

On behalf of TAQA, capacity auctions of SBUs are organised by ICE (ENDEX), the primary market place for TTF futures trading. ICE also organises the platform for secondary trading of storage products. Secondary trading products include SBUs, but also, separately, injection, withdrawal, space and gas-in-store. For example, for a specific delivery period (let us say November 2016) a trader can sell gas-in-store at €25/MWh, buy TTF futures at €24/MWh, buy injection capacity at €0.5/MWh. After deducting injection costs of 0.25 €/MWh as well as transaction and clearing fees (€0.05/MWh), a profit of €0.2/MWh is made.

PANEL 15.3 AECO HUB GAS STORAGE PRODUCTS

NISKA operates two large gas storage assets in the state of Alberta in Canada, Suffield and Countess. The total storage service has a capacity of 154 bcm (billion cubic metres) in working volume, which is filled in 56 days and released in 51 days. On the back of these facilities NISKA's subsidiary, AECO Hub, offers storage services to players in the AECO trading hub, directly connected to the Nova pipeline system. In contrast to European pipeline systems, in Alberta no charges apply to entry or exit of gas storage facilities.

Any storage nomination to AECO Hub is directly delivered on the Nova Inventory Transfer (NIT) virtual trading point, also known under the name of AECO. The NIT offers trading opportunities with the AECO storage service. Whereas Rough and Bergermeer mainly offer standard storage products that closely mimic the actual characteristics of their facilities, at AECO Hub all storage deals are customised.

INTRINSIC AND ROLLING TRADING STRATEGIES

Market price trends

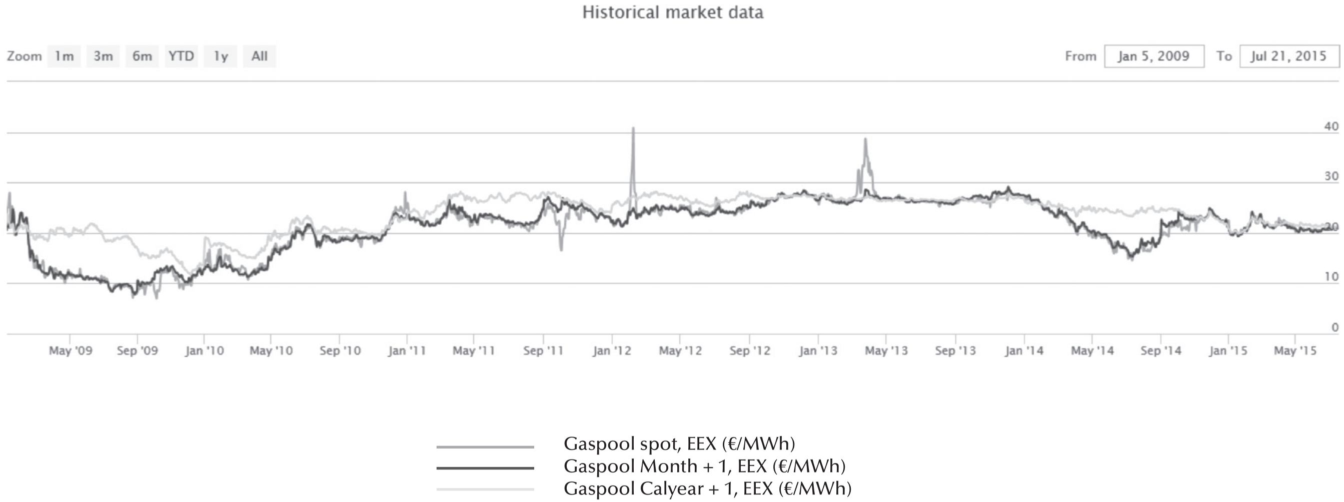
Optimal operation of a storage facility comes down to finding the right time periods on which to withdraw and inject gas, depending on current and expected future gas prices. In short, two characteristics of gas prices allow a storage operator to maximise value:

- ❑ predictable price variations (seasonality); and
- ❑ unpredictable price variations (volatility).

Seasonality is generally considered to be the major source of profits: for example, buying in cheap summer periods and selling in expensive winter periods. However, completely relying on expected price movements ignores the real option, or flexibility, value of storage. For example, even though we observe high prices today, we may optimally wait a few days for even better prices. Similarly, some extra gas may be stored today to be prepared for some extra (unexpected) profitable days of high prices in the future.

Figure 15.1 shows the price development from 2009 to 2015 of different products traded for delivery on the German Gaspool virtual trading point. The graph provides insight into the different dynamics of market prices: day-ahead spot price, front-month forward price and front-year forward price. To begin with, prices have moved in a bandwidth

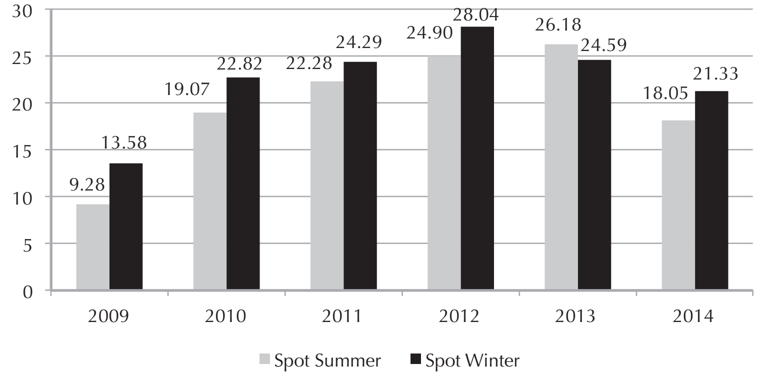
Figure 15.1 Gaspool natural-gas price development



Source: KYOS Analytical Platform

of roughly €10–40/MWh.[2] Just before the financial crisis, end of 2008, prices were highest, then dropped sharply, but recovered gradually. On a few occasions the spot price diverged from the front-month price, especially during two cold spells in February 2012 and March–April 2013. But, other than that, the spot price stayed relatively close, or was mean-reverting to the front-month forward price. The front-month price was more variable than the front-year price, both because the front-year is not subject to seasonality and because delivery is further in the future.

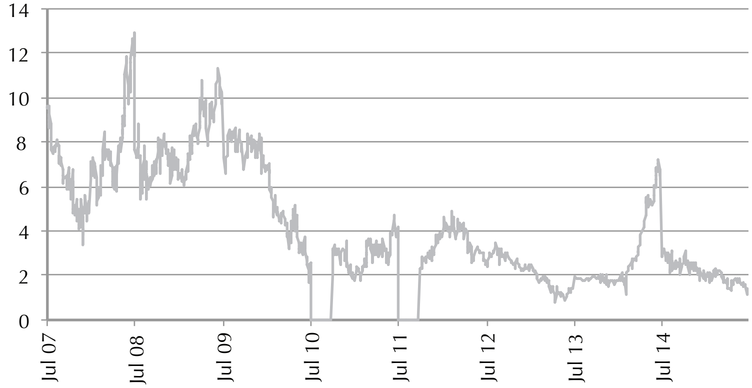
Figure 15.2 Average Gaspool spot prices in summer (Q3) versus following winter (Q1), in €/MWh



Source: EEX

Storage value is largely dependent on differences between summer and winter prices. Figure 15.2 shows the average realised spot prices in summer of that year (third quarter) compared against the prices in winter of the following year (first quarter). Except for 2013, winter prices were always a few euros higher. In Figure 15.3 we can see that this stable pattern of the realised winter–summer spot spread is somewhat misleading: in the forward market the same winter–summer spread is quite volatile. It has also dropped sharply from levels of about €8/MWh to about €2/MWh (note that in two periods, July–September 2010 and July–September 2011, the required Q+6 forward was not yet traded; in the graph this shows as a 0 spread). This has been a general trend in European gas markets and negatively affected storage value. In North American markets, storage traders have gone through difficult times as well, due to very low market prices and correspondingly low spreads. At the same time, this situation has forced gas market players to strive more than ever for the optimal management of the storage using the best trading and valuation approaches.

Figure 15.3 Gaspool forward spread between the next summer (Q3) and the subsequent winter (Q1), in €/MWh



Source: EEX

In this and the following sections, three approaches to gas storage valuation are discussed:

- ❑ the intrinsic trading strategy;
- ❑ the rolling intrinsic trading strategy; and
- ❑ the full option strategy, involving spot trading and delta hedging.

All of these approaches assume a specific trading strategy to realise the storage value in the market and are primarily "asset-backed". This means that the trader is able to fulfil their trading obligations by means of the storage asset: whatever gas they buy can be injected and whatever gas they sell can be withdrawn from the storage. Non-asset-backed trading strategies are essentially speculative and do not help to understand storage value. As we will see, in certain cases a full asset-backed strategy is not possible, though, due to specific asset characteristics, limited market liquidity and/or risk considerations.

Storage is not used only to trade in the market. Individual companies may reap specific benefits from a storage service, to balance within-day volume fluctuations, for instance, or to provide security of supply. The market-based methodologies provide an objective valuation approach that is feasible for a wide variety of storage users, also the ones who do not actively trade in the market. If carefully applied, and considering all costs and uncertainties, the market-based methodologies provide a fair value of what a company should be willing to pay for a storage.

Market-based approaches are useful for valuations within the tradable horizon of typically one to three years out. For longer-term valuations and in particular investments in new physical storage assets, the results must be interpreted with care. Any assumed long-term price forward curve or volatility forecast inevitably involves a lot of guesswork: for example, derived from expectations about fundamental supply–demand balances.

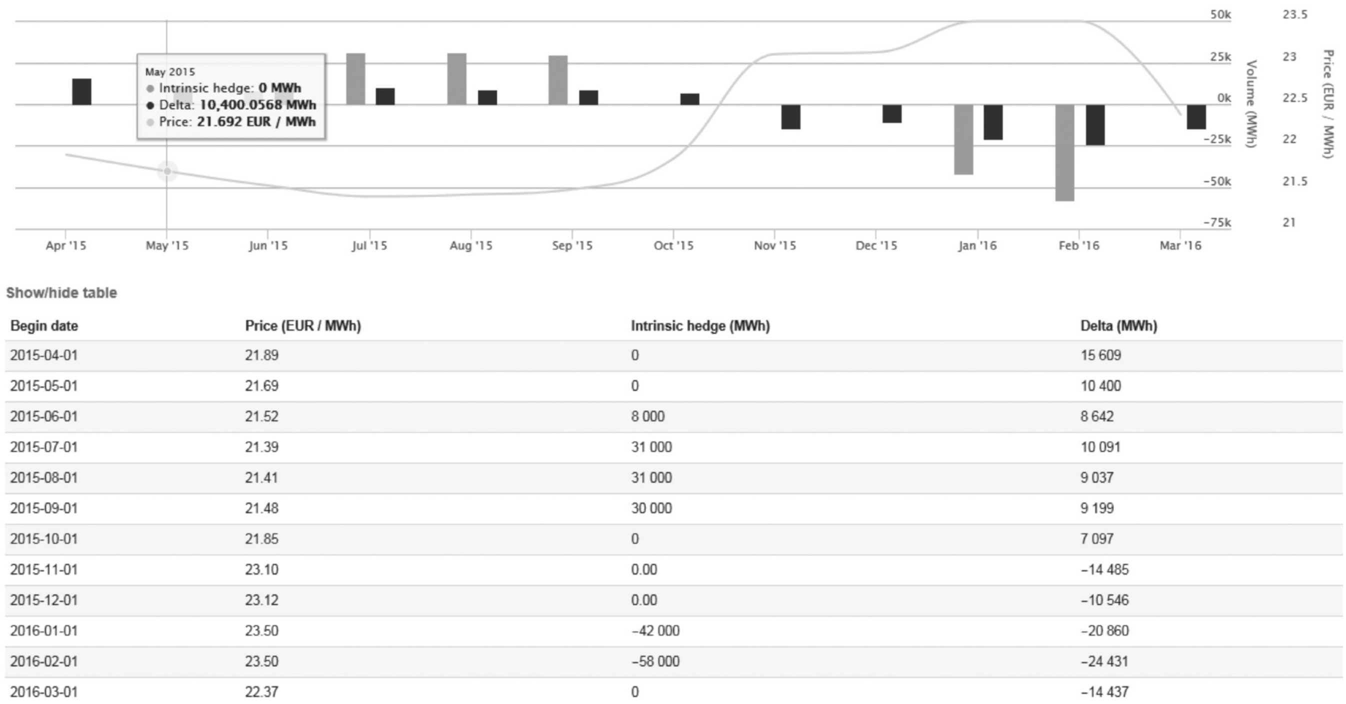
Intrinsic trading strategy and intrinsic value

The intrinsic trading approach exploits the predictable seasonality in the gas markets to buy in cheap seasons and sell in expensive seasons. Of course, both trading costs and operational costs, as well as all sorts of storage constraints and risks, need to be taken into account when calculating the "intrinsic value". Intrinsic value can mean both the value that can actually be locked in in the market or the value derived from a daily or monthly shaped forward curve of which not all pricing points are actually tradable in the market.

When the storage has fixed injection and withdrawal rates, calculation of the intrinsic value is quite straightforward, though we should not forget to include all cost elements. A small example is helpful. Suppose we have a storage product on the German NCG market for the storage year 2015 (running from April 1, 2015, to April 1, 2016). The working volume is 100,000 MWh, daily injection rate 1,000 MWh, daily withdrawal rate 2,000 MWh and variable injection cost €40ct/MWh.

Based on a monthly shaped forward curve (top grey line in Figure 15.4) and the optimal intrinsic injections and withdrawals (light grey bars in Figure 15.4), the intrinsic value of this product is €156,640. This can be decomposed as follows:

Figure 15.4 Monthly intrinsic and delta hedges of a storage valuation[3]



Begin date	Price (EUR / MWh)	Intrinsic hedge (MWh)	Delta (MWh)
2015-04-01	21.89	0	15 609
2015-05-01	21.69	0	10 400
2015-06-01	21.52	8 000	8 642
2015-07-01	21.39	31 000	10 091
2015-08-01	21.41	31 000	9 037
2015-09-01	21.48	30 000	9 199
2015-10-01	21.85	0	7 097
2015-11-01	23.10	0.00	−14 485
2015-12-01	23.12	0.00	−10 546
2016-01-01	23.50	−42 000	−20 860
2016-02-01	23.50	−58 000	−24 431
2016-03-01	22.37	0	−14 437

Source: KYOS Analytical Platform

- ❑ planned injections in July (31,000 MWh), August (31,000 MWh), September (30,000 MWh) and June (8,000 MWh) at an average price of €21.43/MWh and total cost of €2,143,360;
- ❑ planned withdrawals in January (42,000 MWh) and February 2016 (58,000 MWh) at a price of €23.50/MWh and total revenue of €2,350,000;
- ❑ transaction costs of €5ct/MWh on all trades (€10,000), and injection costs of €40ct/MWh (€40,000); and
- ❑ total margin of 206,640 – 10,000 – 40,000 = €156,640.

There are several factors that potentially reduce this monthly intrinsic value. In particular, the gas that is bought in June to September will remain in store for about half a year before it can be sold in the market in January and February the following year. This requires about half a year financing of the total value of gas in store. Storage operators and financial institutions often offer attractive terms for such financing as part of collateralised agreements. Still, financing costs of, for example, 3% annually may apply and reduce the value by about €32,500. In case of higher financing costs it may be beneficial to postpone the injections. For example, even though the October forward price (21.85) is a bit higher than the June forward price (21.52), with financing costs of 5% or more it is better to shift the June injections to October. Other value-reducing factors may include administrative costs, clearing fees and potential unavailability (interruptions) of the storage service. Finally, if the storage service does not include direct entry or exit to the gas trading network, then these costs need to be considered as well.

It may not be possible to fully lock in this monthly intrinsic value today. In particular, the months January and February of the next year are relatively far out and may not be tradable or not liquid. As an alternative, if the first quarter of 2016 is a tradable and liquid product, the trader could sell it as a proxy for January and February. Because the month of March is typically lower than January and February, the quarter price on the NCG market of March 31, 2015, was €22.90, so €0.60/MWh lower, leading to a further reduction in value of €60,000. If intrinsic value is based on what can really be locked in today in the market, it is called tradable intrinsic value. It is a useful conservative definition of value for relatively short horizons, but not for longer horizons than about one year, because then it may not even be possible to lock in any winter–summer spread.

When a storage has injection and withdrawal rates that vary over time or vary with the volume in store, a fully asset-backed intrinsic trade may not be possible. Many storage assets have an injection rate that slows down with higher volumes, or a withdrawal rate that slows down with lower volumes. In storage services this volume-dependence is often incorporated, either with one or more ratchets or with a linear decrease from a certain level onwards. Our example storage could be modified so the injection rate goes down from 1,000 to 500 MWh per day when the inventory is more than 50% full. Following the intrinsic trading strategy, injections in the August may initially be 1,000 MWh per day, but then need to fall, and fall further in September, to 500 MWh per day. This means that for the intrinsic trading strategy in both August and September, after having bought a block forward, a storage trader will have to buy in the spot market additional volumes early in the month and sell spot volumes later in the month.

Rolling intrinsic trading strategy

The intrinsic valuation approach does not reveal all the value of a gas storage. It does not take into account that storage offers the flexibility to adjust injection and withdrawal decisions over time. There are basically two approaches for optimal decision making: rolling intrinsic and real option. Both approaches can combine both spot and forward trading. The key difference is that rolling intrinsic trading decisions are made on the basis of the current market prices only, whereas trading decisions following the real-option approach (described in the next section) take into account that prices are inherently volatile.

With a rolling intrinsic strategy, the trading decisions are more straightforward than with real options: in principle, as soon as a set of trades leads to an immediate (asset-backed) profit, it is executed. For example, the storage holder may be long in the July-16 contract, short in the Q1-17 contract, anticipating injections in the summer and withdrawals in the following winter. He has locked in a spread equal to the forward price difference, the basis for the intrinsic value. When later on the August-16 contract becomes cheaper than the July-16 contract, swapping the summer positions is a profitable roll: sell July-16 and buy August-16 instead. This generates a certain profit equal to the price difference, which comes on top of the initial intrinsic value.

Figure 15.5 Example of rolling intrinsic trading sequence, leading to a total profit of 487.5

Initial position		Jul-16	Aug-16	Q1-17
Trading date: 31 March 2016	Price	20.00	21.00	23.00
Intrinsic value: 300	Trade	100.00	0.00	-100.00

Roll trade 1		Jul-16	Aug-16	Q1-17
Trading date: 15 June 2016	Price	16.00	15.00	25.00
Roll profit: 100	Trade	-100.00	100.00	0.00

Roll trade 2		Q1-17	Jan-17
Trading date: 1 December 2016	Price	25.25	26.00
Roll profit: 75	Trade	100.00	-100.00

Roll trade 3		Spot	Feb-17
Trading date: 10 January 2017	Price	25.50	26.00
Roll profit: 2.5	Trade	5.00	-5.00

Roll trade 4		Spot	Feb-17
Trading date: 11 January 2017	Price	25.00	26.00
Roll profit: 10	Trade	10.00	-10.00

A similar trading opportunity may arise when the individual months of January, February and March 2017 become tradable. If the January-17 price is the highest, the trader could buy the Q1-17 contract and sell the January-17 contract. Finally, in July 2016, if spot prices are above August-16 forward prices, rolling intrinsic could involve selling every day a bit of the long position (or even more than that so as to withdraw) and buying small volumes of Aug-16 forward at the same time. With specific trading dates, market prices and trading volumes, this example is worked out in Figure 15.5.

To trade on a rolling intrinsic basis, the optimal set of trades is calculated each day, with the current trading positions as a starting point. A roll is executed whenever a change in time spreads exceeds the costs for the roll. In practice, traders may define a minimum roll profit or only roll-forward positions several times per year, in order to avoid excessive transaction costs destroying most of the profit opportunities. The optimisation of the intrinsic trades, as well as the subsequent roll trades, can be defined as a linear programming problem. If the trades have to correspond to specific lot sizes, then the program becomes mixed-integer.

Rolling intrinsic is a popular trading approach in practice. The concept is easy to understand and the trader always has a "safe" asset-backed position. In order to assess the profitability over the lifetime of the storage, a Monte Carlo simulation of prices is required. In each simulation and for each possible rehedge date, the Monte Carlo simulation should generate a spot price and a forward curve. Then the model calculates which combination of rolls generates a profit, if any. This is the new trading position until the next trading date, separately for each simulation.

In order to obtain a reasonable rolling intrinsic value, it is essential to operate a price simulation model generating realistic scenarios of future spot and forward prices. In particular, a one-factor model, whereby all price changes on the curve are driven by changes in the spot price only, is not realistic enough: it will not create scenarios with curve changes as we see in practice, except for the short end of the curve, and hence underestimate the rolling intrinsic value. On the other hand, a simulation model with too many risk factors implies too much potential for changes in the curve shape and hence overestimates the rolling intrinsic value.

As an alternative to the Monte Carlo simulation approach, a quick approximation of rolling intrinsic value could be obtained with a spread option model. For example, a trader may identify upfront that it is not unlikely that the July–August spread will turn from negative to positive. Having a short July position initially, such a spread change is an opportunity for a future roll, the expected payoff of which can be approximated with Margrabe's formula (or similar spread option formulas). Essentially, the flexibility of a storage may be considered a basket of spread options, and the valuation approach commonly known as "basket-of-spreads". It is not a very accurate approach, mainly because only a few spreads can be considered. For example, the July–August and July–September spreads are mutually exclusive: swapping July for August precludes the option to swap July for September. And, likewise, the August–September spread option (potentially valuable) is conditional on exercising the July–August spread option first. In short, the basket-of-spreads approach ignores this type of path-dependency, a central characteristic of a gas storage. Nevertheless, as a quick and dirty approach, traders may like it.

REAL OPTIONS: SPOT TRADING AND DELTA HEDGING

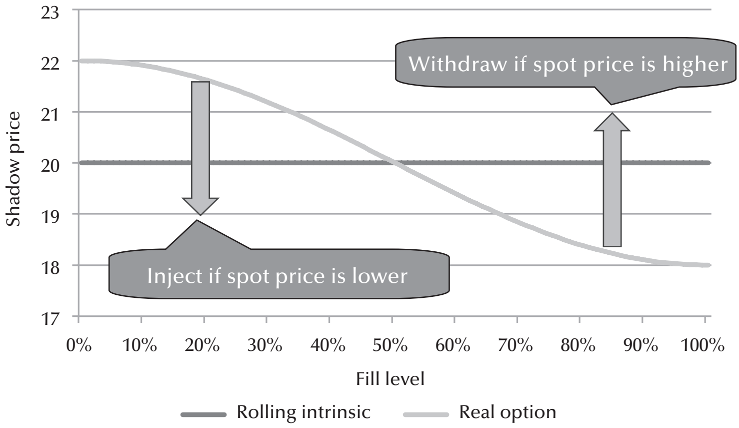
Spot trading

The real option acknowledges that market conditions may vary over time, and incorporates this knowledge in trading decisions. Because spot prices are most volatile, the approach is best applied to spot trading. Nevertheless, it also affects forward trading decisions. A small example may clarify the main idea.

Suppose that the forward curve is flat, at a price level of €20/MWh. If today's spot price is above €20/MWh, the intrinsic approach will advise to withdraw gas from storage and sell in the spot market. Likewise, if the spot price is below the forward price level, the intrinsic trade is to buy in the spot market and inject into the storage. A real-option approach may lead to a different optimal action, depending on the current inventory level and depending on the volatility of future spot and forward prices. In general, when the storage is close to empty, it will more quickly advise to inject in order to increase the flexibility of future decisions ("create optionality"); when the storage is close to full, it will more quickly advise to withdraw.

More generally speaking, considering the volatility in prices, the real-option approach acknowledges that it is attractive to keep both types of options open: to withdraw and to inject. It is therefore optimal to stay away from the boundaries of the storage, because that is where either type of option is reduced in value. Of course, if short-term prices are low enough, it is optimal to inject, anyway, and, if short-term prices are high enough, it is optimal to withdraw, anyway. The shadow prices (or "opportunity prices" or "trigger prices" or "exercise boundaries") will generally follow the pattern as shown in Figure 15.6: higher when the storage is relatively empty and lower when the storage is relatively full. In this figure no variable trading-related or variable storage-related costs are reflected: incorporating these costs would lead to a lower exercise boundary for injections and a higher exercise boundary for withdrawals, creating a price range in between where it is optimal to do nothing.

Figure 15.6 Comparison of exercise boundary for a rolling intrinsic strategy and a real-option strategy



The timing of spot decisions is naturally more effective if based on both current and potential future price levels. This value of volatility is the essence of all option markets and gas storage is not very different. Currently, the most popular real-option valuation approach for gas storage and swing options is least-squares Monte Carlo (LSM or LSMC). It combines Monte Carlo price simulations with accurate and fast least-squares regressions. It is somewhat more computationally intensive (a few seconds for a one-year storage on a standard computer) than tree-based approaches, but it is flexible and precise. Carriere (1996) set out the idea for least-squares Monte Carlo, a method that was later popularised by Longstaff and Schwartz (2001). Two years later (de Jong and Walet 2003) we described for the first time the application to gas storage. Since then, analysts have increasingly applied LSMC to value complex financial and physical options, including other energy assets such as power generation. The method allows market players within a few seconds to estimate the value of a wide variety of storage assets, containing common features, such as injection/withdrawal costs, volume-dependent rates, optional or interruptible rates, time-varying minimum and maximum inventory levels, etc.

Various articles contain detailed mathematical explanations of LSMC and we may refer the interested reader to Boogert and de Jong (2008). In this chapter we provide only a brief explanation and mention a few key features. The LSMC derives the value of a specific gas storage from:

A. the expected future spot prices, mainly reflected by the current forward curve;
B. the potential variations in future spot prices, mainly described by price volatilities; and
C. the current level of gas in store, ie, the inventory level.

Points A and B are incorporated in LSMC first of all by generating a set of Monte Carlo price scenarios, the average of which is equal to the current forward curve ("arbitrage-free simulation"). It is also incorporated in the least-squares regressions: the expected value of storage is a function of specific market prices and the parameters of this function are estimated with least-squares regressions on so-called basis functions of the simulated prices. The regression parameters are estimated separately for each day over the storage horizon, and to capture point C also separately for a representative set of potential future inventory levels. With a recursive backward procedure, the function parameters are derived. Then a forward-stepping approach yields the optimal storage decisions for each Monte Carlo price scenario and each day. In fact, on every day and each scenario, the model computes the highest expected value (including immediate spot cash flows) among the possible actions of injection, withdrawal or no change. The average realised cumulative discounted cashflow across all simulation paths is the storage value.

In natural-gas markets, the forward curve has some predictive value about future spot prices and hence about the expected future value of the storage. For that reason, in addition to spot prices, the basis functions ideally include forward price simulations, such as summer and winter ahead forwards. It also implies that the Monte Carlo simulation engine should generate realistic forward curves, not just spot prices. This leads to a more optimal timing of storage injections and withdrawals and hence higher value. Surprisingly enough, the number of simulation paths does not need to be very high: with about 1,000 scenarios, the storage values are fairly stable, as documented by Boogert and de Jong (2008). Intuitively, the value of storage depends on the cashflows on all days of the lifetime (for instance, one year), not just the payoff on a single day only, as with typical financial options.

A similar remark can be made for another model parameter: the number of inventory levels (grid points) for which the value functions are estimated can be somewhere in the range of 50–200. If the actual inventory level in some simulation paths falls between two grid points, the value can well be approximated by linear interpolation. Especially fast-cycling storage value can be computed with few grid points.

Delta hedging

When the storage trader follows the spot trading signals of this type of storage model, on average they will realise the calculated value. However, that will be at a high risk: winters may be warmer than expected and geopolitical events may push the whole curve in unexpected directions. In order to limit the price exposures, it is essential to combine spot trading with forward hedging. Consistent with a real-option spot trading approach is delta hedging. As with hedging of other options, the hedge volumes aim to neutralise market price movements on the portfolio value.

Suppose we have a storage over a one-year horizon, running from April 1 to April 1 and the real-option value is calculated to be €2 million. The purpose of a delta hedge is to find the optimal trades in the April (this year) to March (next year) contracts. In this context “optimal” means that a change in the forward market price, which affects the storage value negatively by X, is offset by a trading profit in the hedge portfolio of the same amount X. At least for smaller changes in the forward prices, the total change in value of the storage plus the mark-to-market gains of the hedge portfolio should be close to zero. The optimal delta hedges change over time, mainly because of market price movements and because the storage periods go into delivery. If the hedges are adjusted properly over time, the realised value of the storage should be quite close to the estimated value of €2 million, at least when relevant input assumptions (mainly volatility levels) were accurately estimated.

Delta hedges are most directly estimated with a finite difference method. For example, to calculate the optimal hedge of the July product, the July forward price is shifted by a small amount (eg, €0.01/MWh) and the storage value calculated anew (note: the same random numbers or random seed should be used as for the initial run). An increase in the July price (injection period) will, all things being equal, generally lower the storage value, for example by €9,000. The optimal delta hedge is the change in value divided by the change in forward price, in this case (€9,000)/(€0.01/MWh) = 900,000 MWh.

The finite difference is quite computationally intensive, because it requires a storage revaluation (or at least partial revaluation) for each hedge period. For instance, with 12 hedge months, it requires 12 revaluations. Luckily, there are alternative ways to arrive more quickly at (almost) the same solution. Intuitively, the optimal hedge volumes should be quite close to the expected future actions.

Taking again July as an example: if the average decision, across all price paths and all days in July, is to inject 1.0 million MWh, then a good hedge is probably to buy this volume forward. Such a volume-neutral hedge can directly be derived from the initial valuation. To get even closer to the "true" delta is to hedge a volume that matches the value of the average actions. For example, suppose that the forward price for July is €20/MWh. Typically, more volumes will be injected in price scenarios and on days where the July spot price is relatively low. So, the weighted average purchase price in July may be €18/MWh and the average value of the injections in July €18 million. With a current forward price of €20/MWh the delta hedge equals 1 million * (18/20) = 900,000 MWh. With this approach the value-neutral delta hedges have a very logical interpretation and come almost for free out of the main calculation. Furthermore, if the trader buys and sells the delta hedge volumes, the net value of the hedge trades equals the estimated storage value, in this case €2 million.

Figure 15.4 (dark-grey bars) shows the delta hedges (not related to the previous example), which can be compared with the intrinsic hedges (light-grey bars). It can be observed that the delta hedges are more spread out across the periods and not as "extreme" as the intrinsic hedges. Compared with rolling intrinsic hedging, the hedge volumes move more gradually with the market: if the July price goes down (relative to other market prices), more July volumes are bought, every time at a lower price. When the price moves up again, volumes are sold at a higher price. Thereby, the real-option value is gradually realised, eventually also in the spot market. With rolling intrinsic hedging, in contrast, the initial trades lock in the maximum value. Thereafter, one or more new trades are executed, typically with large volumes, if there is a sufficiently large sign reversal in a (tradable) spread.

The delta hedge volumes have one characteristic that may be undesirable: the trades are not fully asset-backed. In particular, in (low-priced) summer periods the hedge volume is lower than in (high-priced) winter periods. This mismatch in buy and sell volumes is larger when prices are more volatile. Companies often have limitations to set up non-asset-backed hedges and a trader may feel uncomfortable, anyway. By the way, this is not a characteristic of storage per se, or of a particular calculation method, just a general characteristic of delta hedges. As a solution and a close proxy to the true hedge, the trader can revert to the volume neutral hedges, ie, the average spot volumes across the simulations (not just intrinsic!).

Using the valuation underlying Figure 15.4, we can demonstrate the characteristics of the delta hedges. Exactly trading the intrinsic volumes in the market leads to a locked-in value of €207,000. When the costs of the storage injections/withdrawals, of spot market trading and of financing are subtracted, we obtain the intrinsic value of around €157,000. A delta hedging strategy ensures gas is already bought forward in the months of April and May, and less (than intrinsic) bought forward in July, August and September. This is with the aim of creating flexibility (having gas in store) and potentially benefit from price variations in any of these periods: buy extra when the price goes down, sell when the price goes up (in forward and ultimately in spot). The total value that is locked in in the market is around €450,000. When the applicable costs are subtracted, we obtain the expected spot trading value of €380,000. In comparison with the intrinsic value, the expected extrinsic value is €223,000.

In the example, the delta hedges are calculated per month, whereas the trader may not be able to trade each month individually in the market, let alone trade the exact delta or intrinsic hedge volumes. First of all, hedges should first be netted with other positions and exposures within the natural-gas trading book. The volumes that remain can be traded in the market, for example with the aim to minimise the total exposure or keep it within specific bounds, often measured volumetrically or by value or by value-at-risk or a combination of these. At the same time, the trade execution should consider the market liquidity of the different trading products, the lot sizes and the associated transaction costs. Specific optimisations that balance both risk minimisation (and / or limits) as well as transaction cost minimisation can aid the trader to execute the best hedges.

VOLATILITY AND OTHER MARKET PARAMETERS

In this chapter we have described three main trading-based valuation approaches to gas storage. All of these lead to an expectation of future income by optimising the storage injections / withdrawals and trading in the market. In practice, once a valuation approach has been adopted, the estimation of the market price parameters forms the main challenge in pricing. Creating an accurate price forward curve is required for all approaches. This may be a relatively simple task in very liquid markets, but becomes a challenge in less liquid markets or longer-term assessments. On top of that, the outcome of the rolling intrinsic valuation and, even more so, the real-option approach depends heavily on the estimated price volatilities, correlations and spot mean-reversion rate. As an example, Figure 15.6 contains the rolling window historical estimates of three market parameters: the spot daily mean-reversion rate, the (annualised) spot volatility and the (annualised) year-ahead or long-term volatility. All estimates are for the German Gaspool, and derived from end-of-day market data of the EEX exchange. The volatility calculation uses an equally weighted history of one-year returns, the mean-reversion rate of two-year returns. In the years 2011 to mid-2015 the long-term volatility has varied between 8% and 28%. The spot volatility showed a similar level of variation, but at obviously higher levels of about 30% to 70%. The spot volatility is also far more relevant for a storage trader. For example, the storage valuation results presented in Figure 15.4 were based on a spot volatility of 50%. With a spot volatility of 25% the storage value is reduced from €380,000 to €254,000. The intrinsic value is €156,000, so the extrinsic value is more than halved. Increasing the spot volatility to 75% leads to an expected spot trading value of €602,000. These results confirm that storage behaves like a financial option, and (speculative) storage trading is a bet on volatility.

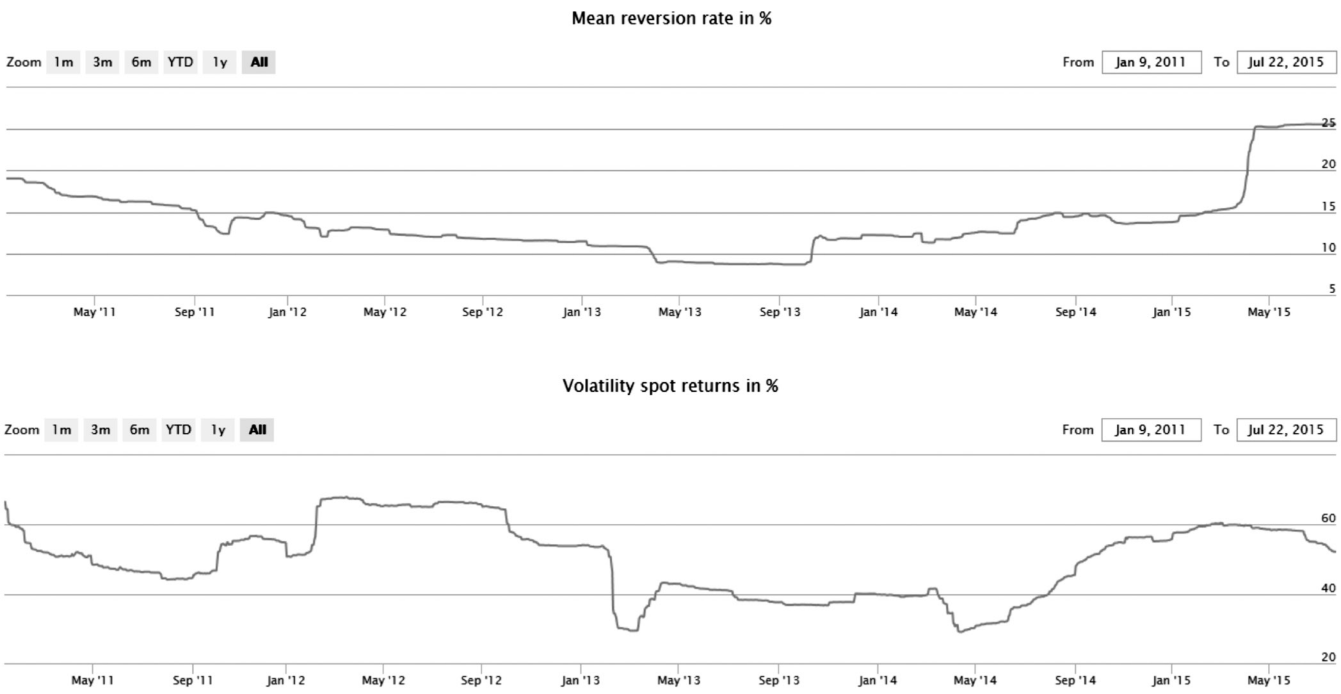
The spot mean-reversion rate is the second most influential market parameter, after spot volatility. Without any mean-reversion, price changes would be completely unpredictable, apart from the seasonality. Without spot mean-reversion the spot price process becomes a (seasonal) random-walk and a storage trader would not be able to make more money than the intrinsic value. De Jong and Walet (2004) show empirically how a relatively low level of mean-reversion (around 5%) could be optimal; higher mean-reversion dampens spot price fluctuations and thus reduces the probability of larger price swings. In particular for seasonal storage assets, low levels of mean-reversion are beneficial, whereas the "optimal" mean-reversion rate for fast-cycling assets is higher. In our example the value of €380,000 is estimated with 10% daily spot mean-reversion rate. Changing it to 5% yields an expected storage value of €463,000; changing it to 30% yields an expected storage value of €297,000. All calculations have been performed with the commercial software KyStore, using the least-squares Monte Carlo approach.

CONCLUSION

Storage is not only a key asset to balance supply and demand, but also an actively traded product in many liberalised markets. Various trading strategies have been designed around gas storage. Individual market players assess if and how storage fits into their books, considering both the value in their own portfolio and the value of asset-backed trading. Asset-backed trading is central to the three different storage valuation approaches discussed in this chapter. Even though a lot of storage capacity is not primarily acquired with the view of market trading, the approaches provide an objective benchmark for valuation.

Of the three approaches, the real-option-based spot trading, combined with delta hedging yields the highest returns. In this chapter we demonstrate the rationale, while a recent article (de Jong 2015) pro-

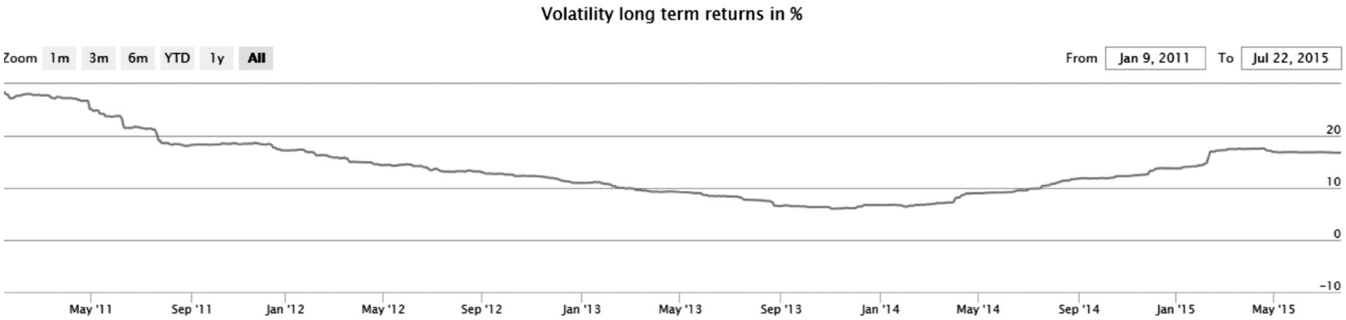
Figure 15.7a, b, c The Gaspool historical market rolling window estimates



Mean reversion rate in %

Volatility spot returns in %

Figure 15.7a, b, c *(continued)*



Note: Figure a contains the mean-reversion rate (two-year rolling window), figure b the spot price volatility (one-year rolling window) and figure c the long-term or year-ahead volatility (one-year rolling window).

vides empirical evidence in a large-scale backtest of gas storage trading in the UK NBP market. The backtest also demonstrates how the value of storage has moved over time: during the period of large winter–summer spreads and high gas price volatility of about 2003–6, gas storage traders could have made a lot of money. In the decade thereafter, market conditions have become far more difficult: storage value is often 20% or less than what it was in the good days. Under tough market conditions, accurate trading optimisation and valuation tools are even more essential to make the most money out of gas storage.

REFERENCES

Boogert, A., and C. de Jong, 2008, "Gas storage valuation using a Monte Carlo method", *Journal of Derivatives* 15 (3), pp. 81–91.

Carriere, J., 1996, "Valuation of early exercise price of options using simulations and nonparametric regression", *Insurance: Mathematics and Economics* 19, pp. 19–30.

De Jong, C., 2015, "Gas storage valuation and optimization", *Journal of Natural Gas Science and Engineering* 23, pp. 365–78.

De Jong, C., and K. Walet, 2003, "To store or not to store", *Energy Risk* (formerly *EPRM*), October, pp. S8–S11.

De Jong, C., and K. Walet, 2004, "Gas storage management", in V. Kaminski (ed.), *Managing Energy Price Risk*, (London: Risk Books).

Longstaff, F., and E. Schwartz, 2001, "Valuing American options by simulation: a simple least-squares approach", *Review of Financial Studies* 11, pp. 597–626.

1 Gas contracts often contain flexibility in the volume that can be taken above or below the contract volume. This is the swing gas volume. Limits on this swing gas volume may be defined per hour, per day, per month, per year, etc.

2 Conversion rates: 1 MWh (megawatt-hour) = 3,600 MJ (megajoules) = 3.412 MMBtu (million British thermal units).

3 See main text for details of the underlying gas storage. Note that the delta hedges are explained under "Delta hedging" later in the chapter.