Anne Neumann *and Georg Zachmann †

Natural Gas Storage in Germany

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*At the time of writing with EE^2 at TU Dresden, now at the German Institute for Economic Research Berlin (DIW Berlin).
†Paris and DIW Berlin.

Abstract T

his chapter analyzes the use of storage capacities in the most competitive European natural gas market and the country with the biggest storage capacities in Europe - the UK and Germany. First, we provide an overview of the German natural gas market with a focus of storage operators. We then develop a simple model which does something based on competitive market participants and the potential merchant use of the facilities. An application to two storage sites shows that it remains unclear whether utilization in 2006 and 2007 was following purely market mechanism or strategic behaviour of operators.

Chapter 1
Natural Gas Storage in Germany

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Contents

1.1 Introduction

Germany is one of Europe's largest natural gas importers and consumers. Given falling domestic reserves, natural gas storage therefore plays an increasingly important role. However, in regulatory terms Germany holds the ȑed lanternı̈n Europe, with very little institutional reform progress and a largely non-competitive gas sector. Subsequently, storage capacities are inefficiently used and the signals for new storage investment are distorted. In this chapter we analyze the structure of natural gas storage in Germany and apply a simple econometric model to see if a particular storage site is efficiently used. The chapter starts with some theoretical considerations about the theory of storage and provides some technical details of storing natural ags. We then introduce the natural gas storage activities in Germany (Section 3). It is dominated by depleted gas and oil fields, but aquifers and salt caverns also play a significant role. The inefficient access to existing storage sites of the incumbents has prompted the new market entrants to invest massively into new sites. In Section 4 we develop a model to evaluate the usage strategy of the observed use of storage with the "perfect arbitrage" solution. By comparing the optimal benchmarking behaviour with the real data, we can infer if the storage market works competitively. In Section 5 we apply the model to real-time data of a large storage site, Dötlingen owned by BEB. We find that A-B-C. Section 6 concludes.

1.2 Theoretical Foundations

1.2.1 Theory of (natural gas) storage

In general, storage is considered a productivity activity transferring a commodity from one period to the next and thereby incurring costs. Consumers holding inventories receive an income stream referred to as convenience becoming due in times of production and/or supply shocks. Therefore, theory implies a difference of spot and forward prices of a commodity at a level given by storage and interest costs (for storing) less convenience yields. Moreover, marginal convenience declines with increasing aggregate level of storage following a convex shape (Fama and French, 1987). The convex shape of the convenience yield implies a modest impact of changes in stock level on marginal costs of storage. Therefore, variations in spot prices are directly related to the benefit of holding inventory and inversely related to the correlation between spot and forward prices. Storage serves to balance short term differences in demand and supply. Entrepreneurial decision criterions for the use of storage are essentially described by: "Store until the expected gain on the last unit put into store just matches the current loss from buying -

or not selling it - now" (Williams and Wright, 1991, p.25). Storage facilities therefore induce arbitraging potential in functioning markets. Traders consider storage as an option derived as the sum of intrinsic and extrinsic values. In other words, the value derived from forward quotations and volatility of spot prices. Wright and Williams (1982) show that storage in a model where production is stochastic and both production and storage are performed by competitive profit-maximizers is favorable for consumers.

Deaton and Laroque (1996) investigate commodity prices for harvest assuming existence of speculators and competitive storage. Defining risk-neutral and profit-maximizing stockholders implies the nexus of spot prices over time periods. The authors show that the effect of storage on prices is only modest, but stronger on the mean and variance of the following period. Wright and Williams (1989) argue that backwardation [2] reflect a risk premium that drives down futures prices. Moreover, they argue that a negative price for storage is a positive difference between full carrying cost and expected rate of change of the spot price.

Markets for natural gas have been of interest for an application of storage theory. This is mainly due to the peculiarities of energy sources as compared to wheat or coffee: natural gas storage is limited by technical factors influencing operability of facilities induced by geological and technical characteristics, and strong seasonality. However, the existence of a number of spot markets (with futures and options traded at) for natural gas and the intertwining of former regionally segmented markets in the US resulted in applications of storage theory.

Susmel and Thompson (1997) provide empirical evidence demonstrating that an increase in price volatility was followed by investment in additional storage facilities. The increase of the variance inherent in spot prices (due to changing market structure and institutional framework) theoretically results in an increased use of storage (An increase in volatility increases the marginal benefit of holding inventory). An application to the Californian market for natural gas is provided by Uria and Williams (2005) arguing that injection decisions rather than resulting stock levels respond to price differences ("despite official seasons, regulatory requirements, and operational rigidites"). Using daily flow data the authors show that injection in Californian facilities increases slightly with a strengthening intertemporal spread on NYMEX. Serletis and Shahmoradi (2006) test the theoretical prediction that when inventory is high, large inventory responses to shocks imply roughly equal changes in spot and futures prices, whereas when inventory is low, smaller inventory responses to shocks imply larger changes in spot prices than in futures prices. Their tests on North American spot and futures natural gas prices confirm these predictions of the theory of storage.

Wei and Zhu (2006), Dencerler, Khokher, and Simin (2005) and Khan, Khoker and Simin (2005) model risk premiums and the dependence of fu-

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[2] Backwardation refers to a situation in which a commodity's future price for future delivery is below the price for immediate delivery.

tures prices on inventory levels with a focus on mean-reverting behaviour for natural gas among other US commodities. Chaton et al. (2006) develop a model of seasonal natural gas demand taking into account the exhaustibility of the resource as well as supply and demand shocks. In a competitive setting the effect of policy instruments, i.e. tariffs, price caps, are investigated and applied to the North American market.

1.2.2 Technical and economic principles

The technology of underground natural gas storage differs in the physical and economic characteristics of the sites. Deliverability rate, porosity, permeability, retention and capability of a site are the main physical of each storage type. To make operation of a storage site financially viable site preparation, maintenance costs, deliverability rates or cycling capacity are the main features. Key for profitable site operation is capacity and deliverability rate. The more natural gas injected or withdrawn the higher the economics of scale. Flexibility and therefore the ability to react to short-term price signals requires reasonable deliverability.

Depleted gas and oil fields can be converted to storage while making use of existing wells, gathering systems, and pipeline connections. Natural aquifers are suitable for storage if the water bearing sedimentary rock formation is overlaid with an impermeable cap rock. Whereas aquifers are similar to depleted gas fields in their geology they require more base (cushion) gas and greater monitoring of withdrawal and injection performance. Deliverability of the site can be enhanced if there is an active water drive. The highest withdrawal and injection rates relative to their working gas capacity are provided by salt caverns. Moreover, base gas requirements are relatively low. Constructing salt cavern storage facilities in salt dome formations is more costly than depleted field. But the ability to perform several withdrawal and injection cycles each year reduces the per-unit cost of gas injected and withdrawn.

The fundamental characteristics of an underground storage facility distinguish between the characteristic of a facility (i.e. capacity), and the characteristic of the natural gas within the facility (i.e. inventory level). Total natural gas storage capacity is the maximum volume of gas that can be stored in an underground storage facility the physical characteristics of the reservoir, installed equipment, and operating procedures. Total natural gas in storage is the volume of storage in the underground facility at a particular time. Base gas (or cushion gas) is the volume of natural gas intended as permanent inventory in a storage reservoir to maintain adequate pressure and deliverability rates throughout the withdrawal season. Working gas capacity refers to total storage capacity minus base gas. Working gas is the volume in the reservoir above the level of base gas and is available to operators/storage customers. Deliverability is a measure of the amount of natural gas that can be delivered (withdrawn) from a storage facility on a daily basis (often referred to also as deliverability rate, withdrawal rate, or withdrawal capacity. Deliverability varies, and depends on factors such as the amount of natural gas in the reservoir, the pressure within the reservoir, compression capability available to the reservoir, the configuration and capabilities of surface facilities associated with the reservoir, and other factors. It is highest when the reservoir is most full and declines as working gas is withdrawn. Injection capacity (or rate) is the complement of the deliverability and is the amount of natural gas that can be injected into a storage facility on a daily basis. It is inversely related to the total amount of natural gas in storage (EIA, 2004).

Depending on the type of storage, investment costs, lead times and operating costs differ. There are no exact figures on natural gas storage sites available, but Grewe (2005) provides some good estimates which are presented in Table **??**

Table 1.1 Storage Costs

	DGF/DOF	Aquifer	Salt cavern
Specific investment costs per m^3 working gas [/m^3]	0,18 - 0,33	0,38 - 0,40	0,54 - 0,65
Specific investment costs in withdrawal rate [/m^3]	11,4 - 22,7	26,5 - 34,8	13,6
Total costs per cycled m^3 working gas p.a. [Euro cent/m^3][1]	5,86	6,73	9,81
Total costs per (m^3/ day) withdrawal rate p.a. [/(m^3/day)/a][2]	3,82	5,87	1,99

[1] Capital costs plus fix and variable operating costs.
[2] Capital costs plus fix operating costs.
Source: Following Grewe, 2005.

1.3 Germany in the European natural gas system

Germany is a net-importer of natural gas. In addition to 12% domestic production, natural gas is imported from mainly four countries: Norway (12%), Netherlands (45%), Russia (34%) and UK/Denmark (23%). The role of natural gas storage is therefore essentially defined as to balance (seasonal and short-term) demand and to secure supplies in times of supplies. The geographic location in North-western Europe with connections to the major transit pipelines and short-term trading places favors the use of natural gas storage facilities to benefit from short-term arbitraging possibilities.

Germany accounts for 123 bcm of working gas capacity and is therefore a major storage nation in Europe. The biggest European storage facility Epe is located in the western part of the country, operated by 3 companies and has 123 bcm working gas capacity. 8 percent of the total working gas capacity (WGC) is located in aquifers which are geographically well spread over the country. Caverns provide 35% of total WGC and are mainly located in the North-Western, Eastern and Central (at the intersection of the MIDAL and STEGAL pipelines) parts of Germany. The main share of WGC (57%) is provided in depleted oil and natural gas fields (DGF, DOF). These storages sites are centred in Southern and spread in North-Western Germany. A few are located in central Germany and in South-Western Germany.

Table 1.2 Natural Gas in Germany (2007)

	Quantity (bcm)	Share of toal imports
Domestic	14.3	
Netherlands	19.13	22.85%
Norway	23.74	28.36%
Russia*	37.95	45.33%
UK	2.90	3.46%

* including other Europe and Eurasia
Source: BP, 2008.

The existing working gas volume in Germany has more than doubled since 1990 and provides a total working gas capacity of 18.45 bcm (nearly the whole Dutch imports). The following section provides a description of storage types in Germany and Figure 1.3 shows the locations.

Aquifers

Total capacity of aquifers in Germany is 2.796 Mio. m^3. The smallest facility contains 60 Mio m^3, the largest 630 Mio. m^3 and on average they have a total capacity of 350 Mio. m^3. The total working gas capacity is 1.489 Mio. m^3 and thus around half of total capacity. Aquifer storage sites are the smallest storage facilities with regard to WGC in Germany. The average Q_{max} injection rate is at 169.000 m^3/h, the lowest is 45.000 m^3/h, and the highest 400.000 m^3/h. The biggest aquifer is located near Berlin. It has 780 Mio. m^3 working gas capacity and is owned by Berliner Gaswerke AG, a distribution company jointly owned by Gaz de France International S.A.S., Vattenfall Europe AG and Thüga AG. Verbundnetz Gas AG owns another aquifer in this region (175 Mio m^3) which allows the company to store some of the imported natural gas from Russia. In the Western part of Germany close to the Dutch border RWE Netzservice GmbH operates a site which holds 215 Mio. m^3 working gas capacity. E.on Ruhrgas AG, Saar Ferngas

Fig. 1.1 Location of storage sites in Germany

Source: Sedlacek, 2007.

AG and Gasversorgung Süddeutschland own an aquifer close to the river Rhine where advantageous geological conditions allow storing some 262 Mio. m^3 working gas capacity in total. Aquifers in South-West Germany near the cities Frankfurt/ Main, Mannheim and Heidelberg are situated close to the pipeline-junction MIDAL and SÜDAL.

Depleted gas and oil fields

Storage in depleted gas and oil fields (DGF, DOF) is less flexible. Total working gas capacity in Germany amounts to 10.876 Mio. m^3. The smallest facility contains 40 Mio. m^3, the largest 4.200 Mio. m^3 and on average they have a total capacity of 725 Mio. m^3. Total capacity nearly doubles working gas capacity. Total available working gas capacity amounts to 2.566 Mio. m^3. The average Q_{max} extraction rate is 313.000 m^3/h, the lowest is 45.000 m^3/h and the highest 1.200.000 m^3/h. Most of the DGF are owned by natural gas importing companies, i.e. Wingas GmbH, BEB GmbH, E.on Ruhrgas and RWE DEA AG. Most of cavern storage sites are located in the Northwestern part of Germany in a large gas field which stretches from the North Sea and the Netherlands into Hamburg. Southern Germany, in the region Munich and Rosenheim is home to five depleted gas storage sites with a total working gas capacity of 3.350 Mio. m^3 located in a large gas field which stretches from Vienna (Austria) to Munich.

Cavern storage

Natural gas storage in (salt) caverns is the most flexible and allows frequent injection and extraction. Cavern storage requires less base gas which allows a higher share of working gas capacity. Total working gas capacity in Germany amounts to 6.700 Mio. m^3. The smallest facility contains 17 Mio m^3, the largest 1.657 Mio. m^3 and on average they have a total capacity of 335 Mio. m^3. Total capacity is 9.062 Mio m^3. The average Q_{max} extraction rate is 570.500 m^3/h, the lowest is 100.000 m^3/h, and the highest 2.450.000 m^3/h. The ownership structure of cavern storage sites is more diversified than for aquifers or DGF. However, there remains a dominant position of market players such as E.on Ruhrgas AG (2.385 Mio. m^3 WGC), Verbundnetz Gas AG (1.441 Mio. m^3 WGC) and EWE AG (1.237 Mio. m^3 WGC).

German natural gas storage facilities are owned and run by 22 storage operators. Wintershall (4.200 Mio. m^3), E.on Ruhrgas (3.925 Mio. m^3), BEB (2.477 Mio. m^3), Verbundnetz (2.231 Mio. m^3) and RWE DEA (1.900 Mio. m^3) operate approximately three quarters of total WGC.

Considering different types of storage facilities shows a more diversified picture. Cavern storage facilites are owned by natural gas importing companies (E.on Ruhrgas AG and Verbundnetz Gas AG), regional transmission companies (EWE AG, Essent Energie Gasspeicher GmbH) and distribution companies (Stadtwerke Kiel AG, Kavernenspeicher Stassfurt GmbH, GHG Gasspeicher Hannover GmbH). However, the regional distribution companies are owned by market players such as E.on Ruhrgas AG, RWE Energy AG and Thyssengas. In essence, the German market for natural gas storage facilities is dominated by five market participants - incumbents from the öldẅorld.

Table 1.3 Key characteristics of German storage sites

Location	Operator	Type	Technical storage capacity (mio m^3)	Peak with-drawal capacity per day	Peak injection capacity per day
Krummhörn	E.on Ruhrgas	Salt cavity			
Epe	E.on Ruhrgas	Salt cavity	1641	58.8	13.4
Hähnlein	E.on Ruhrgas	Aquifer	80	2.4	1.4
Stockstadt	E.on Ruhrgas	Salt cavity / Aquifer	135	3.3	2.2
Sandhausen	E.on Ruhrgas	Aquifer	30	1.1	0.3
Bierwang	E.on Ruhrgas	DGF	1360	28.8	13.3
Eschenfelden	E.on Ruhrgas	Aquifer	72	3.1	0.8
Etzel	ConocoPhillips, E.on Ruhrgas, Statoil/Hydro	Salt cavity	560	31.4	12.96
Döetlingen	BEB Speicher Gmbh & Co.KG	DGF	1076	13.44	12.96
Uelsen	BEB Speicher Gmbh & Co.KG	DGF	520	5.88	5.88
Harsefeld	BEB Speicher Gmbh & Co.KG	Salt cavity	130	7.2	2.16
Rehden	Wingas	DGF	4200		
Kalle	RWE Energy	Aquifer	215	9.6	4.8
Xanten	RWE Energy	Salt cavity	190	6.72	2.4
Nievenheim	RWE Energy	LNG Peak shaving	14	2.4	0.11
Epe	RWE Energy	Salt cavity	414	12.48	4.08
Stassfurt	Kavernenspeicher Stassfurt GmbH	Salt cavity	200	6	2.4
Buchholz	VNG	Aquifer	175	1.92	1.2
Berburg	VNG	Salt cavity	953	34.8	12
Bad Lauchstäedt	VNG	Salt cavity/DGF	1001	24.48	16
Kirchheiligen	VNG	DGF	190	3	3.36
Inzenham-West	RWE DEA	DGF	500	7.2	3.36
Wolfersberg	RWE DEA	DGF	320	5.04	2.88
Breitbrungg/Eggstädt	RWE DEA/ExxonMobil/E.on Ruhrgas	DGF	1080	12.48	6
Peckensen	GdF Erdgasspeicher Deutschland	Salt cavity	60	3	0.84
Huntorf	EWE	Salt cavity	139		
Neuenhuntorf	EWE	Salt cavity	17		
Nüttermoor	EWE	Salt cavity	920		
Schmidthausen	EWE	DGF	150		
Lehrte	Deilmann-Haniel	DOF	40		
Reitbrook	Deilmann-Haniel	DOF	350		
Fronhofen-Trigonodus	GdF Deutschland	Pore-space	36	1.8	0.72
Bremen-Lesum	ExxonMobil	Salt cavity	204	8.64	2.88
Frankenthal	Saar Ferngas	Aquifer	63		
Bremen Lesum	Bremen Stadtwerke	Salt cavity	78		
Berlin	Berliner Gaswerke	Aquifer	780		
Allmenhausen	Contigas	DGF	55		
Kiel-Rönne	Kiel Stadtwerke	Salt cavity	60		
Kraak	Hamburger Stadtwerke	Salt cavity	117		
Reckrod	Gas Union	Salt cavity	82		
Epe	Deutsche Essent	Salt cavity	181	0.4	0.2
		Total	**18388**		

Source: Gas Storage Europe, 2008a.

Regulation of storage facilities

The German Energy Law (Energiewirtschaftsgesetz, EnWG) transposes the Second Gas Directive 2003/55/EC into national law. It aims to provide a secure, reasonable priced and environmentally friendly supply of energy (1 EnWG).

28 EnWG requires access to storage facilities in the area of grid bounded supply of natural gas. Storage system operators have to provide other companies appropriate and non discriminatory access and supporting services if this access is technically and economically essential for an efficient grid access relating to the supply of customers (28 (1) EnWG). However, storage system operators can refuse access if they can prove that access is not possible due to operational or other reasons. Information on access conditions, storage facility location and available capacity has to be made available for interested parties.

In an accompanying ordinance, the Gasnetzzugangsverordnung (GasNZV) indicates that every interested party for using the distribution system shall be granted access to the grid and agreement must be submitted with the one grid operator whose distribution system will be used for line entry or line exit (3 (1) GasNZV). 15 GasNZV lays out the principles of storage capacity request and bookings. Grid operator have to publish a map covering the whole distribution system including all storage facility locations (22 (1) GasNZV).

Forthcoming investments

Taken together, the location of storage sites in Germany is geographically well dispersed. Although most of the working gas capacity is located in North-West Germany, which is required given the German natural gas import structure and based on geographically favourable conditions, there appears to be significantly fewer facilities in the Ruhr region. The regions close to Stuttgart, Ulm and Southern Germany as well as around Dresden seemingly lack the possibility to balance demand at short notice. Planned projects in Germany are listed in Table 3 and are mainly investment in new cavern storage facilities, 15 of which are planned to become operational by 2015. The majority of these planned projects are located close to existing sites. In most cases the ownership structure stays the same to the already existing cavity. It is interesting to note that the only new participant is planning to construct a new site in Epe. The companies in the consortium are mainly municipalities and independent traders. However, overall these investments are undertaken by dominant market players. In total, expected working gas capacity is about 8 bcm and therefore increases the current volume by nearly 45%.

1.4 Market Based Use of Storage Capacities - A Model

The overview of German storage facilities and the corresponding operator in the previous section reveals a significant share of incumbents in the market for natural gas storage. In this section we test the hypothesis that the usage strategy observed at Dötlingen (a large depleted gas field operated by BEB) is not closely related to perfect or liquid market mechanisms. To evaluate the usage strategy of the facility actual storage decisions have to be compared with some benchmark. Therefore, we proceed in three steps: First, we define the storage optimization strategies. Second, we calculate the behavior

Table 1.4 Expected Investment into storage facilities

Location	Operator	Type	Investment	Expected WG capacity	Expected Date
Etzel	E.on Ruhrgas	Salt cavity	New facility	2500	2013
Kiel-Ronne	E.on Ruhrgas	Salt cavity	New facility	50	2015
Etzel	EdF Trading / EnBW	Salt cavity	New facility	360	2011
Epe	Essent Energie Gasspeicher GmbH	Salt cavity	New facility	200	2011
Epe 2A	Essent Energie Gasspeicher GmbH	Salt cavity	Expansion	110	11/2008
Huntorf	EWE	Salt cavity	New facility	150	2015
Nuentermoor	EWE	Salt cavity	New facility	180	2015
Ruedersdorf	EWE	Salt cavity	New facility	300	2015
Reckrod	Gas Union	Salt cavity	New facility	50	2015
Anzing	GdF Erdgasspeicher Deutschland	Reservoir	New facility	165	2013
Behringen	GdF Erdgasspeicher Deutschland	Reservoir	New facility	1000	2013
Peckensen Phase 2	GdF Erdgasspeicher Deutschland	Salt cavity	New facility	160	2010
Peckensen Phase 32	GdF Erdgasspeicher Deutschland	Salt cavity	New facility	180	2014
Empelde	GHG	Salt cavity	New facility	110	2015
Wolfersberg	RWE DEA	Reservoir	Expansion	45	2010
Xanten	RWE Energy	Salt cavity	Expansion	125	2015
Frankenthal	Saar Ferngas	Aquifer	Expansion	130	2015
Epe	SPC Rheinische Epe Gasspeicher GmbH & Co. KG / Essent Energy Productie B.V.	Salt cavity	New facility	365	2010
Bernburg	VNG	Salt cavity	New facility	300	2015
Jemgum	Wingas	Salt cavity	New facility	1200	2015
Reckrod-Wolf	Wintershall	Salt cavity	New facility	120	2015
		Total	**8080**		

Source: Gas Storage Europe, 2008b.

given the defined strategy (benchmark). Finally, we compare the benchmark behavior with the observed strategy. [3]

1.4.1 Defining storage optimization strategies

For simplicity we define the two main strategies "perfect market" and "imperfect market". The "perfect market" strategy is characterized by full price taking behavior of the storage user. Therefore, the profit function can be written as $\Pi = \sum \Delta v_t p_t - c(\Delta v_t, p_t, V_t)$ where Δv_t is the storage decision, p_t the price and $c(\Delta v_t, p_t, V_t)$ are associated cost at time t. The "imperfect market" strategy assumes that the storage user faces decreasing marginal payoffs when selling at high prices. This might be due to an illiquid market or strategic behavior, i.e. arising opportunity cost for reducing the price

[3] This section draws on previous work where we compare storage operation in the UK and Germany (Zachmann and Neumann, mimeo). The basic idea is that a competitive market such as the UK will use natural gas storage according to the theory of storage.

for volumes sold from other sources. Those effects usually become important when markets are already tight and thus prices are high and in particular volume-elastic. In our "imperfect market" benchmark case we model these effects by a "mark-down" $md(\Delta v^{-}{}_{t}, p^{+}{}_{t})$ depending on the price and storage decision. Thus the profit function of a storage user becomes $\Pi = \sum \Delta v_t p_t$-$c(\Delta v_t, p_t, V_t)$-$md(\Delta v^{-}{}_{t}, p^{+}{}_{t})$.

1.4.2 Calculating the behavior under defined strategies (benchmark)

In a second step, we calculate the storage user's strategy. This is done by maximizing its profit with respect to stochastic prices, a non-linear cost function, non-linear constraints and (depending on the strategy) a non-linear mark-down. Before presenting the algorithm the core components of the profit optimization are introduced.

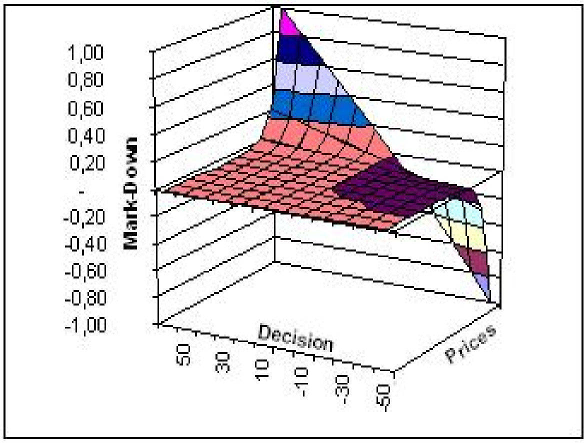
Specification of technical constraints

A storage facility is essentially characterized by three factors: the injection rate, the withdrawal rate and the working gas volume (maximum less minimum volume). We consider the maximum and minimum observed storage level as best proxy for the real upper and lower constraints. This approach has the advantage that not only the purely technical constraints are included but also non-technical obligations e.g., such as strategic reserves in case of bad whether, are incorporated. Maximum injection and withdrawal rates are more difficult to deduce as those generally depend on the storage level. If, for example, a storage facility is close to its capacity limit it is technically more difficult to inject natural gas and if almost empty, withdrawal rates decline. Taking this behavior into account we estimate the corresponding relationship using observed data. Therefore, we first extract the maximum injection and withdrawal speed for each storage level. Then we estimate the relationships between maximum injection rate and storage level, and between maximum withdrawal rate and storage level using a polynominal (see Figure 1.4.2).

Specification of cost function

The cost function consists of four components: fuel cost, injection cost, withdrawal cost and storage cost. *Fuel cost* (fc) is a symmetric percentage (ϕ) of injections/withdrawals used for injection/withdrawal. Used fuel is valued at

Fig. 1.2 Standardized mark-down (a=1; b=100)



current prices and the fuel cost component is written as fc_t=ϕ*Δv$_t$*p$_t$ (Δv$_t$ is the storage decision). *Injection/withdrawal costs* (ic/wc) are additional cost depending only on injected/withdrawn volumes: ic_t=μ_i*Δv$_t$ if Δv$_t$>0 and wc_t=μ_w*Δv$_t$ if Δv$_t$<0. Finally, *storage cost* is the cost for holding gas in store: sc=ς*V_t. The assumptions for the four cost components are taken from Simmons (2000) and presented in Table 4.

Table 1.5 Assumptions for the four cost components

Fuel used at each injection/withdrawal (ϕ)	1%
Cost associated to each injection (μ_i)	0.02 $/MMBtu
Cost associated to each withdrawal (μ_w)	0.02 $/MMBtu
Cost for holding natural gas in store(ς)	0.40 $/MMBtu

Source: Simmons, 2000.

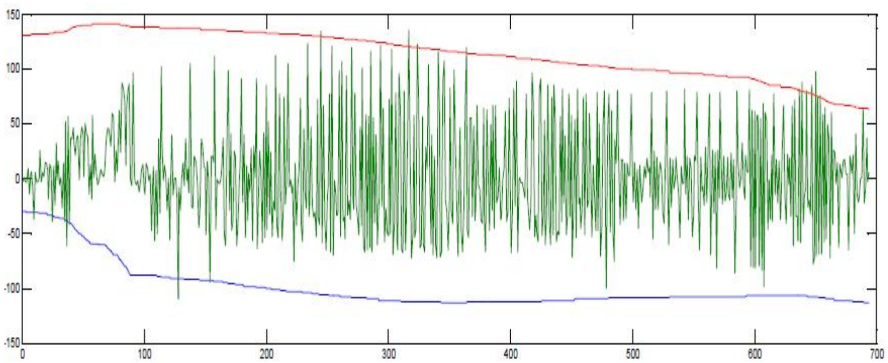
Specification of mark-down

In order to calculate the optimal behavior in the "imperfect market" case we assume that: i) market prices are not exogenous but react on the injections/withdrawals of the storage user; ii) prices react increasingly sensitive on volume changes when supply is tight (and thus prices are high); and iii) some storage users optimize a portfolio of natural gas assets. Thus, overall profit is negatively affected by decreasing prices. Therefore, storage users have to balance payoffs from selling natural gas in store and associated profit-reductions at other sources. Consequently, profit reacts more sensitive on price decreases due to withdrawals than price elasticity would imply. To keep the model simple we propose a two parameter specification of the "imperfect market mark-down" as illustrated in Figure 1.3:

$$MD(p,$$

ΔV)=a*f(p)*g(ΔV) with $f(p_t)$=b$^{-((max(p)-p_t)}$/(max(p)-min(p))) g(ΔV)=ΔV/max(ΔV),$\forall\Delta$V$\geq$ 0ΔV/min(-ΔV)$\forall\Delta$V<0

Fig. 1.3 Observed injections/withdrawals (green) and corresponding estimated maximum injection (red) / withdrawal (blue) rates)



Specification of price expectations

To optimize its day-to-day injection/withdrawal decision a storage user needs to have some knowledge on future price developments. Futures and forward prices should represent the best guess of future spot price development, that can be represented by the so-called price forward curve (PFC). This PFC is calculated based on current futures prices. While weekly or monthly futures are traded near to spot month, seasonal or annual futures are traded for longer time horizons. Thus the PFC is calculated by smoothing and adding seasonalities (see Figure 4).

Nevertheless it is clear to all market participants that future spot prices will generally deviate from the PFC. Therefore we assume natural gas spot prices to be stochastic in the short run while reverting to the corresponding PFC in the long run. The related parameters (mean reversion speed, volatility) are estimated using real data.[4]

The optimization algorithm

Different optimization algorithms for maximizing the profits from natural gas storage usage have been proposed in the literature. Generally two approaches can be distinguished. While solving a Bellman equation provides a closed form solution given certain price generating functions, Monte Carlo simulations are very flexible with respect to constraints and price models but have no analytic solution.

To cope with a nonstandard price function (reversion to moving mean) as well as nonlinearities in constraints and cost we follow Boogert and de Jong (2006) applying a Least Square Monte Carlo approach to natural gas storage contracts. Since identifying the optimal storage strategy is comparable to locating the exercise date of American options, Boogert and de Jong (2006) apply an option valuation algorithm proposed by Longstaff and Schwartz (2001). The general idea of the concept is to optimize storage usage decisions backwards in time using a discrete (daily) time grid, a discrete volume grid and n simulated price paths. The volume grid stretches from minimum to maximum storage level at equal distance volume steps: Vol_{min}:$VolStep$:Vol_{max}. These volume steps are defined to approximately represent a tenth of the daily decision spectrum (i.e., the difference of maximum injections and maximum withdrawals). Thus, at each day and volume combination, around ten different decisions are possible (cf. Figure 1.4.2).

Time-values for a discrete set of allowed strategies are compared at each decision making point. Consequently, we first define a termination date and the payoff function at this date. We set the termination date $T=t_0+365$ (that is one year after the start date), and the payoff function at T is defined depending on the volume in storage at termination date (Vol_T). If the volume exceeds a desired level (Vol^*) the payoff is zero. We assume that a user has to pay a punishment of double the time-value of the missing volume if the critical level Vol^* is undercut. This yields:

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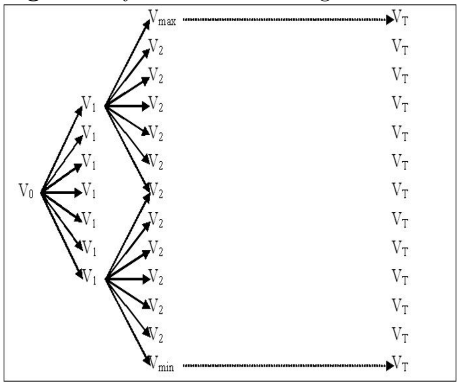
[4] In an application to the UK market Haff et al. (2008) find a non-linear effect of storage on the relation of spot and futures prices.

Fig. 1.4 Stylized discrete storage



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