Energy Strategy Reviews 25 (2019) 65–74

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

A financial option perspective on energy security and strategic storage

Lawrence Haar[a,*], Laura N. Haar[b]

[a] Oxford Brookes Business School, Oxford Brookes University, UK
[b] Manchester Business School, Manchester University, UK

ARTICLE INFO

Keywords:
Energy security
Strategic inventories
Financial options and risk neutral density functions

ABSTRACT

On the whole, research into energy security falls into one of three perspectives: The political perspective, the engineering and geologic perspective, or the economic perspective emphasising market resilience. Common to these perspectives is the emphasis upon examining exposure to supply disruption, but not its probability of occurrence. As petroleum markets have shown themselves generally resilient to secular events and actual disruptions rare, despite perennial concerns, we ask if our understanding of security cannot be improved? We apply financial option theory to three eventful periods to learn the expectations of market participants on the probability of disruptions. We find the forward-looking views of petroleum market participants to be accurate with regard to both price persistence and the resilience of markets in absorbing shocks. Our results cast doubt upon the need for emergency inventories unless justified to dampen market volatility on public good grounds.

1. Introduction and background

Energy security is a recurring theme in the design of energy policy even though there is no consensus on how it should be measured, achieved or the relevant time frame over which it should be assessed. In contemporary literature we find three alternative perspectives: the sovereignty perspective originating in political science; the "robustness" perspective originating in the natural sciences and the "resilience" perspective with its roots in financial-economics [1]. All three perspectives to assessing energy security draw upon one or more of the following sets of criteria advanced by the Asia Pacific Energy Research Centre [2,3]:

a. Availability (incorporating geologic or technical elements)
b. Accessibility (involving social and political elements)
c. Affordability (comprising financial-economic factors)
d. Acceptability (embodying environmental or social factors)

Elaborating upon these criteria, for example, if a nation were importing a large proportion of its petroleum from a politically unstable country as Venezuela or depended upon supply from a declining resource like the North Sea, it would be observed that the nation faced *accessibility* and *availability* insecurity. Diversified sources of petroleum imports from stable regions but at *unaffordable* prices would contribute to supply insecurity [4]. If, on the basis of *acceptability*, relying upon nuclear energy became problematic, then a country dependent upon imports of Liquefied Natural Gas (LNG) to generate electricity (e.g. Japan) or pipeline gas (e.g. Germany) would face supply insecurity [5]. Utilising these criteria, bodies such as the US Geologic Service compute reserves to production ratios as an indicator of energy security [6]. Other researchers have proposed metrics for both diversity of sources and import dependence [7]. Combining the second and third criteria, some researchers have used the World Bank survey of governance and published country credit ratings to indicate the security of a supplier, although its usefulness is uncertain. In 2015, Russia's credit rating was reduced to junk debt status by Standard & Poor but for over 40 years the country has continued to be reliable exporter of natural gas supplies to Western Europe. Meanwhile, Nigeria a country beset with governance issues where current production has fallen by 25% from earlier peaks, but it has remained a reliable exporter and its Bonny Light crude, a global benchmark. Recognising the limitations of individual metrics, the International Energy Agency developed a Security Supply Index [12] combining criteria from the three perspectives. Their Index includes sources of supply (pipelines versus bulk crude carriers) and measures of market concentration in sources of supply.

Focusing upon the *resilience* perspective on energy security, economic factors such as prices, volatility and liquidity, figure strongly. Discussions involving economic factors and in particular resilience to shocks often look at short-term demand and supply elasticity, the availability of buffer stocks and the scope for consumption management. The role of market liquidity, the ease of executing large trades without moving prices, is also considered [8]. Looking at how energy is

* Corresponding author.
E-mail addresses: lhaar@brookes.ac.uk (L. Haar), laura.n.haar@manchester.ac.uk (L.N. Haar).

https://doi.org/10.1016/j.esr.2019.100364
Received 15 August 2018; Received in revised form 3 February 2019; Accepted 7 May 2019
Available online 31 May 2019
2211-467X/

used in an economy, various frameworks and metrics have been proposed to indicate oil market vulnerability [9]. Other researchers have considered the scope for demand-side management to address energy insecurity [10]. Recognising differences in prices, income elasticity and reservation prices by countries, an aggregate index was constructed to predict the ability to absorb or withstand a supply disruption [11]. In this case, a higher reservation price and deeper pockets, indicate less supply insecurity. Notwithstanding the insights to be gained from using such economic criteria, it remains difficult to draw rigorous inferences on either energy security or what is needed as a strategic reserve.[1] Critically, such metrics do not tell us the probability of a disruption occurring, focusing instead on vulnerability or exposure. Consider, for example, in 2014, when the price of West Texas Intermediate dropped to below $50 per barrel from a high of $112, markets still cleared and remained in equilibrium. Clearly, capturing the International Energy Agency's (IEA) own definition of energy security as “the uninterrupted physical availability at a price which is affordable”, in single metric or index, is not easy.

Moving from metrics and indices to full-scale models for simulation, we can distinguish between long and short-term models to assess energy security and exposure to supply disruptions. The Global Energy Analysis Systems of the IEA, the MARKAL/TIMES model is designed to explore at a global and regional level, alternative scenarios for energy technology and climate policies. Using the MARKAL model, entire energy system may be modelled, depicting all possible flows of energy from resource extraction, through energy transformation and end-use devices, to demand for useful energy services. In the United States, the DOE-EIA has its National Energy Modelling System (NEMS) which generates a general equilibrium solution of the interactions between the U.S. energy markets and the economy and which may be used model changing sources of supply. But using long-term, technology rich models to represent short-term supply insecurity and the impact of disruption may be problematic. In 2011, the IEA introduced its Model of Short-Term Energy Security (MOSES) for primary energy sources and secondary fuels among IEA members [12]. MOSES examines short-term energy security: defined as vulnerability to physical disruptions that can last for days or weeks. Taking an energy systems approach, MOSES identifies a set of indicators for external risks (from energy imports) and for domestic (from transformation and distribution) as well as for resilience – a country's capacity to accommodate different types of disruptions. In MOSES, a policy parameter is introduced to calibrate energy security according to national priorities; a sort of social welfare function for risk tolerance. Focusing upon physical disruptions, MOSES excludes economic issues such as affordability and energy price volatility. Using the IEA's MOSES model, energy security may be ranked according to five categories from most to least secure. MOSES offers a framework for conceptualising policy discussions on energy security: it depicts basic conditions of supply and demand at country level and facilitates inter-country comparisons. If a country wished to change basic conditions, the Model may be used to inform policy making. Like some other metrics, the focus of the MOSES is upon the short-term impact of volumetric loss to supply and, in some instances, upon the ability to mitigate or absorb the loss. These approaches, however, do not tell us about the probability of a supply disruption or how the market participants view security.

Summarising, we see that many approaches been developed to conceptualise and assess energy security from interesting metrics and indices to large structural models. Approaches involving individual metrics may involve supply and demand, looking at resource estimates, the ratio of imports to domestic production or measures of economic structure such as producer concentration, energy intensiveness and market conditions. Their focus tends to be at country or regional level even though petroleum is a global market and chains of supply are highly flexible. Large-scale, technologically rich simulation models in which economic agents can respond to price signals, undertake investment, change patterns of consumption, are useful for long-term planning and policy guidance, but may have limited scope for capturing the effects of short-term disruptions. The MOSES model, meanwhile is suitable for measuring the effects of disruptions along with how strategic inventories may enhance economic resilience in the face of supply interruptions. Altogether, these efforts are interesting and tell us much about vulnerability and resilience but do not tell us about the *probability* of a supply disruption taking place. On the whole, these models focus upon exposure to disruption and the ability of a nation or region to absorb the impact of such an event. Energy security is not conceptualised as the probability of a disruption occurring. Altogether, this is interesting because, in the insurance and finance literature*, three* parameters are used to characterize a risk: the exposure to potential loss if the event occurs, the scope for mitigation or loss absorption within a specified time frame *and* the probability of the event happening.[2]

Looking at the probability of supply disruption may be important because we repeatedly see major events in oil market which appear capable of interrupting *physical availability at a price which is affordable*. In 2016 we saw sabotage in Kirkuk, a strike in Kuwait, the Canadian wildfire, Nigeria's force majeure, export blockage in Libya, Colombian pipeline disruptions, Italy's Val d’Agri shut down and fire at Brazil's Barracuda-Caratinga site. Although serious events, none of them led to disruptions or affected oil prices which traded within a range of $26 and $54 per barrel. The same could be observed for 2017, despite OPEC's production cuts, market liquidity was unaffected [13,14]). In 2018, the wave of political protests across Iran along with sanctions led to sharp declines in production but global markets for oil remained stable, with Brent trading between $50 to $86 per barrel. Looking back in history, during the Suez conflict of 1956, oil production from the Middle East was reduced by approximately 1.7 million barrels per day in November of that year, but we saw only a short effect, with production restored to normal by February, 1957 [15]. The cutbacks associated with the Iranian Revolution in 1978-89 led to no global oil supply disruption despite many worrisome predictions [16].

Interestingly, when disruptions to supply have taken place and consumption affected, we find that government intervention was pivotal. We recount the supply disruption in the summer of 1951: as an orchestrated response to the Iranian nationalisation of their oil industry, a global boycott of its production was carried-out which removed 19 million barrels per month of production from global markets. The effects of the boycott were exacerbated by the US domestic price controls in place during the Korean Conflict [15].[3] Similarly, it has been argued that the impact of 1973–1974 Arab Oil Embargo, including the long queues for transportation fuels in major US cities at the time, were exacerbated by the Nixon Administration price controls in force since the collapse of Bretton Woods and the mis-allocation of transportation fuels between Petroleum Administrative Districts (PADS) by the US Department of Energy [17]. In sum, recent and historical events show both the resilience of the global petroleum markets and the role of official actions [15,18]. In the examples shown, despite various shocks and questionable policies, the frequency of supply disruption remains small.

On the question of storage, it is common sense that such reserves make an economy more resilient to supply disruption but how much is

[1] In contrast, inventory optimisation models and solutions have as inputs, forecast attaching probabilities to various events such as sales in order to model expected costs and benefits.

[2] On the supply-side, according to the risk assessment framework developed for the US Department of Energy (DOE), by the Stanford University Energy Modelling Forum, there is a 63% probability of a long-term oil market disruption between now and 2025 [48]. Their method is Delphic.

[3] The Texas Railroad Commission, the oil and gas regulator, contributed to the size of disruption by limiting crude output [18].

required? Concerns over supply security prompted the European Commission to conduct in 2014, a stress test to Europe's dependence upon imported crude oil (90%) and natural gas (60%) and recommended a variety of measures to mitigate the impact of disruption [50]. More generally, the countries of the OECD follow the IEA's 90-day import replacement guidance on minimum stockholding requirements. But is this sufficient or is it wasteful? If the purpose of storage is loss-mitigation, the various models we have reviewed facilitate comparing costs with benefits but ignore the probability of strategic inventory being needed. Indeed, the wisdom of examining a loss potential and the scope for mitigation without attaching a probability to the event seems questionable. But given the infrequency of supply disruption events, how can one construct a probability distribution suited to assessing economic insecurity and resiliency?

To examine the probability of disruption, we propose using the information found in traded option prices to quantify the probability of supply-demand imbalances, disruptions and energy market security. Introducing the probability of disruption into the measurement of energy security from the resilience or economic perspective, given the paucity of data, has always been problematic. To address this challenge, we introduce a fresh approach employing financial option theory. As commodities, markets for crude oil, petroleum products and natural gas hold the attention of countless agents seeking to secure supplies, hedge exposures, speculate and take advantage of anomalies through arbitrage, we argue that markets sui generis provide insight into energy security. Reflecting market sentiment, prices for oil may be at times volatile and other times less volatile. Usefully, the forward-looking nature of option markets embody the views of participants upon prices in the future. Employing a method first proposed by Ross [19] and developed by Breenden and Litzenberger [20]; we utilise the second derivative of the option pricing formula to compute the risk neutral density (RND) functions for expected future prices. As we explain below, information from option prices, allows us to obtain market expectations of oil prices in the future. From traded petroleum options, we can see how participants view future market conditions including the security of supply. The proposed method uses the principles of risk neutral pricing, but we do not ignore the policy implications of varying degrees of risk aversion [21].

In Section 2, Methods and Data, we explain how the risk neutral density function is obtained from option prices. We use published data from the International Commodity Exchange (ICE) for the crude oil bench-mark of Brent. To examine the merits of physical storage from the standpoint of volatility reduction (as opposed to economic resilience), we use data for the US Department of Energy for the world's largest strategic storage, the Strategic Petroleum Reserve (SPR) of the United States. In Section 3, we show and interpret our results, examining market perceptions of future prices during three key historic periods. Using the Samuelson criteria (1954) for the optimal provision of public goods, we analyse the expected distribution for future oil prices according to financial option theory to compare the benefits of price volatility reduction with the costs of physical storage, learning when it may be justified.[4] We conclude in Section 4 with some policy suggestions on energy security, its measurement and management.

2. Methods and data

2.1. Loss Expectation versus loss exposure

As explained above, discussing a loss magnitude within the context of energy security without attaching probability to the event seems questionable. In the financial field, it akin to focusing upon Loss Given Default or Exposure at Default but ignoring the probability of the event-Loss Expectation. Indeed, insurance markets would not exist if actuaries could not attach probabilities to loss events. Surely discussion of energy security and vulnerability to disruption would be enhanced through including the probability of an event taking place? But as explained above, with so few market disruptions having occurred, despite repeated shocks, how can we construct statistics on the probability of an event occurring? Appealing to market efficiency arguments, we propose using option prices to capture relevant and available information on future market conditions including the potential for short and long-term disruptions [22,23]. Arguably, if the global market for petroleum were facing a sustained and sizable reduction in daily output, regardless of country specific conditions such as dependence upon imports, reliance upon pipelines versus tankers or energy intensiveness of GDP, the threat of disruption and supply insecurity, the expectation of loss, like all market conditions would be embodied in prices [24]. We show that using the information embodied in option prices, allows us to examine energy security probabilistically, enhancing our understanding of potential exposure or vulnerability or even the scope for mitigation. Below we explain how.

2.2. Option prices and risk neutral probabilities

To introduce the Expectation of disruption into the discussion of energy security, and thereby enhance discussions of exposure and vulnerability, we use the risk-neutral densities derived from option pricing models in order to learn how participants, view market conditions. Of course, examining prices is not new. Analysts and market technicians have long tried to discern future market conditions from various transformations of historic prices with varied success. For example, looking at markets, estimates of the risk of disruptions during the First Gulf War, for example, have varied by as much as a factor of five [25]. The infrequency of interruptions, however, makes actuarial inferences difficult. In contrast to examining historic data, the extraction of risk neutral densities from option prices provides a forward-looking estimate of future market conditions. To explain our method, we begin by reviewing option theory.

As background, options are priced using risk-neutral valuation and require five parameters: market prices, strike prices, volatility, time and interest rates. Risk neutral valuation means that the prices of options are invariant to subjective risk preferences, risk aversion or subjective market views. They provide an objective market driven view of risk: how it is priced, mitigated and transformed. As we see in the Black-Scholes-Merton differential equation (Appendix 1), the specification using the above parameters are independent of individual risk preferences. Theoretically, options may be priced as though the world were "risk neutral". So even if some consumers, businesses or nations were "risk adverse", i.e. willing to pay more than the expected actuarial cost of disruption to hedge against price increases or to maintain storage, the theoretical valuation according to option theory, would remain unchanged (Hull, pages 293–294, 2006). Indeed, most economic agents display varying degree of risk aversion. Depending upon their utility functions: risk aversion may be constant, decreasing or increasing and risk-neutral results may be adjusted using risk premia to obtain subjective measures of probabilities [26–28].

Usefully, in the pricing of options, traders require a premium for options which are not at the money. The premium increases with the difference between the strike price and the market price. This premium is known as the volatility "smile" and increases the aforementioned extrinsic value of the option, as illustrated in Fig. 1 below. It uses the greater implied volatility observed for options which are not "at-the-money" according to the theory developed by Rubinstein [27]. The greater price for an option which is not "at-the-money", implies greater volatility: the market is thinner and traders command a premium to the at-the-money option price. Usefully for our purpose, risk-neutral probability distributions (RNDs) of future asset returns may be derived from the option model and provide an ex ante estimate of the

[4] Volatility is annualised measure of standard deviation in prices commonly computed over a relevant historic period.

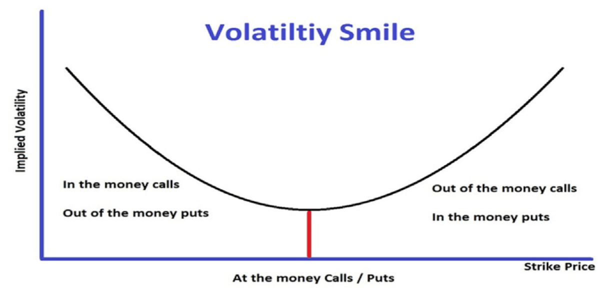

Fig. 1. Volatility smile (source: https://www.thebalance.com/volatility-skew-2-2536781).

underlying asset price at the maturity date of the option.

According to received theory, the price of an option at maturity is equal to the present value of the expected value of the terminal payoff assuming no arbitrage and risk-neutrality. For a Call Option we have the following expression at time τ = T-t:

$$c(t, X, \tau) = e^{-r(t)\tau}E_t[\max(S_T - X, 0)] = e^{-r(t)\tau}\int_X^{\infty}(s - X)\pi_t(s)ds \tag{1}$$

Where St = time-t underlying price, rt = time-t continuously compounded financing rate, Et[.] = expectation at time-t risk neutral probability measure and πt(.) = time-t risk neutral probability density of ST. Differentiating the price of the Call Option with respect to the strike price, X, we obtain the exercise price or Delta:

$$\frac{\partial}{\partial x}c(t, X, \tau) = e^{-r(t)\tau}\left[\int_0^X \pi(s)ds - 1\right] \tag{2}$$

According to equation (3), the time-t risk-neutral cumulative distribution function of the future asset price, that is the probability that the terminal underlying price will be X or lower, is equal to the one plus the future value of the exercise-price Delta of a European Call Option with an exercise price of X:

$$\prod_t (X) \equiv \int_0^X \pi_t(s)ds = 1 + e^{r(t)\tau}\frac{\partial c(t, \tau, X)}{\partial x} \tag{3}$$

Now, taking the second derivative of the Call option price with respect to the exercise price, the Gamma, gives us the time-t risk neutral probability density function:

$$\pi_{t(}(X) = e^{r(t)\tau}\frac{\partial^2 c(X, \tau, t)}{\partial X^2} \tag{4}$$

This is the market's risk-neutral probability of future prices. The summation of the products of probabilities and strike prices, X, computed along the volatility smile, as shown in Fig. 1, from deeply in-the money to at-the-money to deeply out-of-the-money yields the probability of the weighted expectation of future prices. Using the implied volatility function, we have obtained the risk-neutral expectation of future prices.[5]

The price difference between two options on the same asset but at different strike prices on, for example, Brent Crude Oil, may be used to learn the market view of where prices will be in the future, at contract expiration. From traded option prices, we can obtain ex ante probabilities of future prices. The second derivative of option prices provide information on how agents perceive market conditions, specifically the probabilities attached to various strike prices [20] or [29]. Thus, using option theory we learn the market perception of expected future prices. Next, we address the data challenges in this method.

[5] In Excel, we use the VBA Add-Ins from the DerivGem to compute the Gamma Values (http://www2.rotman.utoronto.ca/~hull/software/index.html).

2.3. Data

In order to implement the above method, we need traded option prices at a sufficient number of strike prices both above and below the current spot price, to construct a probability density function or histogram. We use public data from ICE relating to the traded Brent Oil contract, taking daily observations beginning in 1997 to the present, although we only report results for certain periods. Although the ICE traded benchmark Brent crude oil contract is one of the world's most liquid securities, at any given time, apart from strike prices which are at-the-money options, there may not be quotes on a full range of options at in-the-money and out-of-the-money strike prices. Deeply in-the-money and deeply out-of-the money options may not appear and modelling the tails of histograms presents challenges [30,31]. Computing risk-neutral probability distributions of future oil prices from the implied volatility smile requires traded options, to be quoted on a given day and expiration, with a sufficient number of strikes. Further, options may not be traded at equally spaced intervals. To address the problem of option prices not quoted in sufficient quantity of in-the-money or out-of-the-money strikes, consistently over time, as needed to construct a volatility smile and ultimately arrive at the probability weightings for various strikes, several different methods of volatility smile fitting such as cubic spine interpolation or parametric method are used [32]. Others have suggested interpolating call price functions directly [33]. We follow the approach of interpolating in the implied volatility domain and take the implied volatility surfaces from ICE using their arbitrage-free interpolation method.[6] The respective volatilities are then used as inputs to Equation (4) to obtain risk-neutral probabilities for respective strike prices along the volatility smile. The probability weighted sum of the strikes gives us the market expectation of future prices. Importantly, although options may be priced theoretically as explained above, Equation (1)., we use actual market data from ICE. Without loss of generality, with an expiry date of one-half year to be sufficiently forward-looking, yet with sufficient liquidity.

Introducing the probability of disruption into analysis of energy security, we examine the argument for physical storage considering Strategic Petroleum Reserve (SPR) of the United States, the world's largest strategic reserve. Following IEA guidance, the SPR, with a storage capacity of 727 million barrels has 74 days of import replacement (9.8 million barrels per day) or 165 days of import replacement at 4.4 million barrels, using the maximum rate of export. Together with state and private crude and product storage, the SPR satisfies the IEA guidelines for security of supply [34]. To compare the benefits of storage with its costs, we use an opportunity cost of capital of 3% employed in maintaining physical storage, plus the additional operating costs for the SPR which adds approximately 10% to the price of crude oil [48]. Although the price of crude oil to fill the SPR varies with time, we mark-to-market the value of reserves at the contemporary price to make comparisons with expected future prices according to option theory at the same point in time.

3. Results

3.1. Option theoretic price forecasts

We now turn to the predictive densities calculated through applying option theory to the aforementioned volatility surfaces. From the implied volatilities of observed prices, as depicted in the smile, we obtain the market's risk-neutral probabilities of various strike prices, from which we can obtain market expectation of future prices. According to efficient market theory, this expectation should embody all relevant information, including the risk of market disruption and energy

[6] https://www.theice.com/market-data/etd-volatility-surfaces#methodology.

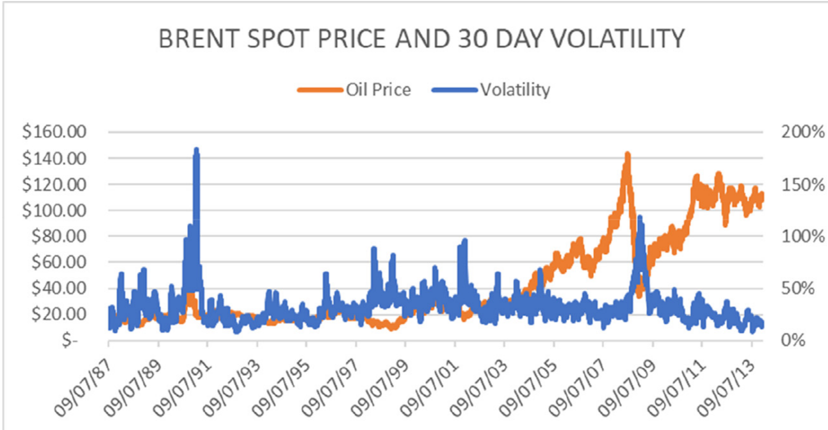

Fig. 2. Historic prices for brent crude and volatility (source: ICE).

insecurity. To provide perspective in our discussion, we show in Fig. 2, daily Brent Crude Prices and rolling 30-day volatilities from 1997 to 2017.

We compute Risk Neutral Probability histograms for the three periods shown below in Table 1 with the results summarised in Table 2 below. The three data sets were chosen because they were times of great uncertainty in petroleum markets with many extreme scenarios suggested. From the probability histograms we can determine the market's expectation of future prices as driven by supply and demand conditions.

Beginning with the implied risk neutral histogram for the Brent Crude Oil prices during the First Gulf War, we see in Fig. 2 below that over the above-mentioned dates, the market expectation of future prices was slightly skewed to the left and displayed negative kurtosis. Although historical market price volatility at the time was high, as seen in Fig. 2 above, and reported in Table 1 averaging for the period 77%, according to the forward-looking results of option theory, according to the risk neutral density results from option theory, the expected price for the year was around $26 per barrel. Notwithstanding many extreme scenarios of how the First Gulf War might unfold [35], evidence that market participants in pricing options, believed disruptions were likely, is not supported and proved prescient. As we see in Fig. 3 below, the probabilities ascribed to tail-events, kurtosis grew smaller as expectations narrowed with time while the distribution flattened. The day after the United States and its allies attacked Iraq, oil prices in London and New York plunged an unprecedented $10.56 a barrel to $21.44 or ten US cents below its price on Aug. 1, the day before Iraq invaded Kuwait, and remained in this range throughout the conflict. It appears that market participants correctly discounted the effect of the conflict upon the threat of supply disruption.

Turning to the 2008 Financial Crisis and using data for the entire calendar year we see in Fig. 4 below that the forward-looking view of the market flattened over time. Emergency policies from Central Banks such as Quantitative Easing were yet to begin and the potential for shale oil in the United States was yet unknown. Accordingly, we see that as the year progressed, kurtosis increased, the distribution grew flatter, with growing market uncertainty. Although the shock-waves from the financial crisis were only beginning to reverberate, probability was still not given to extreme scenarios, such as demand collapsing. As summarised in Table 2 below, according to constructed RND functions, the mean expectation was that oil prices would remain at just over $90 per barrel. As reflected in markets, oil prices during the financial crisis were high but volatility only increased sharply towards the end of the year, reaching 103% for Brent Crude on the 16th of December, this is captured in the flattening distribution seen below in Fig. 4. Although the widening financial crisis added to oil market risks, based upon option prices, market participants were still anticipating reliable supply at prevailing price levels.

Table 1
Data sets.

Data set	Dates	Mean	Mean volatility
The First Gulf War, 1990	15-6-90 to 1-3-91	$26.73	76.87%
The 2008 Financial Crisis	2-1-08 to 31-12-08	$96.94	42.73%
The Arab Spring	1-4-11 to 30-6-11	$117.01	31.73%

During the Arab Spring of 2011, the average prices of crude oil were high while historic volatility was moderate. As the crisis unfolded, by December 2010, some analysts were predicting that the demonstrations in Tunisia would lead to supply-chain disruptions and a sharp rise in oil prices [36]. As unrest spread to other countries, the threat of interruption gained credibility. The IEA coordinated a draw-down of reserves [37] to calm markets. Indeed, the threat of civil unrest spreading to the Gulf, for example, was raised [38]. But there were some dissenting voices: A report from the Oxford Institute for Energy Studies warned against alarmism, arguing that oil markets are remarkably resilient and that the basic conditions of supply and demand were unlikely to change [39]. Similarly, a paper from Chatham House on the Arab uprising reached similar conclusions [40]. Interestingly, from the probabilities derived from option prices, we see in Fig. 5 below a flattish distribution reflecting a divergence of views. According to option markets, the median view was for prices to remain around $120 per barrel. We see throughout the period positive kurtosis, i.e. some weight given to prices going higher but like the dissenting voices, the market appears not to have taken the possibility of extreme prices as would happen through severe disruption to supply, seriously. In contrast to the doomsayers, the market perception was that petroleum markets were sufficiently resilient to weather the various events of 2011 and were already taking-on-board such factors as the continued expansion of US liquids production from unconventional reservoirs, the continuing decline since 2008 of oil demand by the countries of the OECD, the dampening in Chinese growth rates from 10% to 7% and, of course, the resilience of international petroleum markets.

The above results are illustrative: they neither prove that markets are always resilient nor that disruptions cannot take place. But the results support the following points:

a. Through the use of forward-looking price distribution obtained from traded option prices, useful additional insight into energy security may be obtained; and
b. In the periods examined, at least, markets were not anticipating extrema as might occur under a disruption scenario.

As shown in Table 2 below, markets did not expect price spikes and

Table 2
Source: Authors' calculations.

DATA SETS	E(Prices)	Minimum	Maximum	Historic Volatility
1990 First Gulf War - Low Prices, High Vol.	$ 26.32	$ 18.71	$ 34.75	76.87%
2008 Financial Crisis Very High Prices & High Vol.	$ 94.59	$ 67.86	$ 126.03	42.37%
2011 Arab Spring High Prices & Moderate Vol.	$ 115.38	$ 81.91	$ 152.12	31.73%

the prices to which even small probability events were ascribed, were not outliers, viz. 3 sigma events. Arguably, according to forward-looking price estimates obtained from the risk neutral density functions, markets were not anticipating supply disruptions and proved accurate: participants correctly foresaw that market shortfalls or disruptions were unlikely. Even with output from some producers falling, in the periods examined, markets were not anticipating price levels consistent with disruptions or other forms of supply insecurity. From the standpoint of energy security, the focus upon loss potential if a disruption *were* to occur is important, but ignoring the probability of such an event, undermines its utility. Indeed, assessing energy security from the perspective of resilience concentrating only upon exposure while ignoring the probability of a disruption event, may give us a distorted picture. In addition to the insights to be gained from including the *expectation* of losses in analysis of energy security, it prompts questions with regard the needs for strategic storage is needed. For this we turn to the next section.

3.2. The economics of storage

The above results may have implications for the strategic storage as held by many countries of the OECD. Notwithstanding tumultuous events and extreme predictions by some analysts, in the periods examined, the markets anticipated correctly future prices. Probability histograms derived from option prices show extreme oil market prices (as might happen under supply disruption) were not predicted. Although there may be scenarios under which the option implied risk neutral density functions point to extreme prices, at least in the periods examined, markets equilibrated at affordable levels, precluding shortfalls. Unless we believe that market participants discount the probability of disruptions *because* of the existence of strategic reserves-a feedback effect; without other justifications, the resilience of markets, at least in the short-term, casts doubt upon their necessity. But can strategic reserves be justified for other reasons?

Price instability and volatility are inherent to commodity markets and especially petroleum. Since the beginning of modern industrial production of petroleum, prices have fluctuated as one would expect given the vagaries of supply and demand. Although an inter-temporal price trajectory exists in conformity with natural resource theory [41,42], there have always been sources of exogenous perturbations. Such shocks in the form of short and long-term risk factors arising from geology, technology and operational matters affect the prices over time. The discovery of large fields, pre-salt deposits off the coast of Brazil, or enhanced recovery methods, like the shale boom, can shift the long-term price trajectory. By the nature of geologic depositions large amounts of recoverable, economic reserves may arise in a "lumpy" manner, creating discontinuities in the price trajectory. On the demand side, changes in aggregate demand such as technical advances or improved efficiencies, may also affect the price trajectory. Petroleum prices have always been volatile but is there a role for government in reducing or eliminating risk even if the probability of disruption and extreme price scenarios, is small? Like requiring medical insurance or saving for retirement, might expenditure on storage be justified to avoid free-riders? Are negative externalities through insufficient management of risk? Is there a case for reducing risk in petroleum markets and how might it be measured?

Drawing some comparisons with agricultural commodities, the US government, like many governments, has a long history of intervening in commodity markets [43,44]. The US spends annually upon agricultural commodity price support some $25 billion and the European Union some €40 billion on support mechanisms to stabilise prices and ensure adequate income to farmers. Although the SPR was created to address import disruptions, over the years it has been used repeatedly for situations deemed of national importance related to price stabilisation: during the first Gulf War, in 1991, draw-downs were authorised, as well as during Hurricane Katrina in 2005 and Hurricane Harvey in 2017. Following the Libya revolution of 2011, the US Government, in coordination with other OECD countries, released 30 million barrels of petroleum from the SPR (energy.gov/fe/services, 2016). But apart from the above special situations, we ask two questions:

a. Given the resilience of oil markets in responding to tumultuous events, is a strategic reserve needed on grounds of energy market insecurity?
b. Might using a strategic reserve to dampen market volatility, making markets more predictable, through reducing the cost of hedging, be

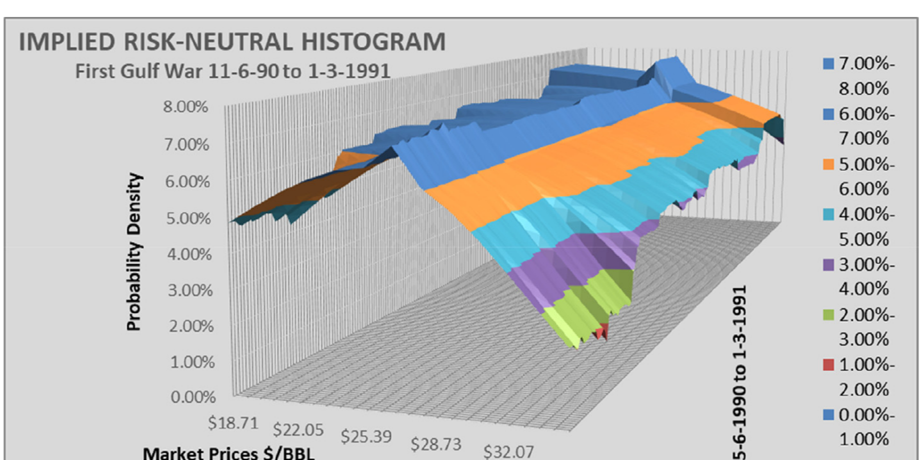

Fig. 3. Implied risk-neutral histogram for brent crude prices, first gulf war (source: Authors' calculations).

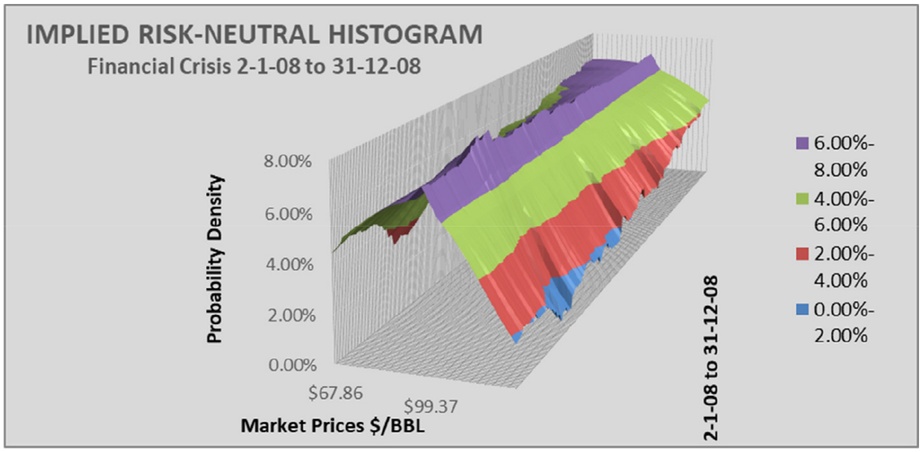

Fig. 4. Implied risk-neutral histogram for brent crude prices, financial crisis (source: Authors' calculations).

justified as public goods?

National storage of crude oil is widely seen as a public good designed to mitigate the impact of severe and sustained import disruption. Yet, petroleum products are both excludable and rivalrous in nature. Privately owned crude oil inventories in the United States frequently exceed 500 million barrels, or about three-quarters of the SPR volume. These observations prompt the question of why governments, outside of national security or defence matters, should store petroleum and whether any additional services, may provide justification? Is there a public good argument for actively managing the SPR to reduce volatility? For example, exporting volume in rising markets and importing volume in falling markets to dampen market volatility and narrow bid-offer spreads, even though market agents have available liquid traded markets in options and futures to manage risks and express complex views. Formally, the decision on how much of a public good (such as risk reduction using a strategic reserve as the SPR) should be produced, requires finding the level of production which equates marginal social benefits with marginal social costs [45].

Upon this supposition we provide the following results. Comparing the costs of maintaining the SPR with the cost of reducing market volatility tells us how much risk reduction is merited. Holding physical storage at a known price is an alternative to risk managing the exposure using options. As options could be used to eliminate or mitigate the risk, they allow us to quantify the benefit of actively using a strategic reserve to dampen volatility. In Fig. 6 below we compare the marginal benefit from risk reduction using the prices of European style of exercise call options with the cost of maintaining the SPR's 9.5 million barrels per day of drawn-down capacity, with a carry cost of 3%.

As shown in Fig. 6, unless volatility is reduced by about 20% (from a volatility by assumption of 50% to a volatility of about 40%), the costs of maintaining the SPR (financing plus operations) are not covered. Although the results can be re-calibrated to a different initial volatility assumption, option theory allows us to measure the benefits of using the SPR for risk reduction. In sum, given our observations on energy market security, ignoring the possibility of feed-back as noted above, the case for maintaining a strategic reserve may be enhanced, if actively used to reduce market volatility. These results assume risk neutrality. If a society were risk adverse and placed a premium on the option-quantified benefits of reducing volatility, then greater levels of market intervention might be justified.

These findings could be extended in two further ways. First, the results ignore the indirect opportunity cost of sub-optimising storage capacity. Private entities own and operate storage facilities with various injection and withdrawal capacities. Their intrinsic value is a function of the combinations of possible spreads between prices when injected versus when withdrawn; its additional extrinsic value is a function of the volatility of crude oil when injected versus when it is withdrawn and the correlation between respective prices. Such assets are commonly valued and optimised as a series of spread options or using sophisticated stochastic dynamic control models to analyse the potential value in having the right to exchange one risky asset for another risky asset over time [46,47]. According to assumptions for volumetric capacity, lifting and withdrawal constraints, volatilities and correlation, such models tell us the potential value to be derived from using a storage asset. To the extent that the SPR with a capacity of nearly 700

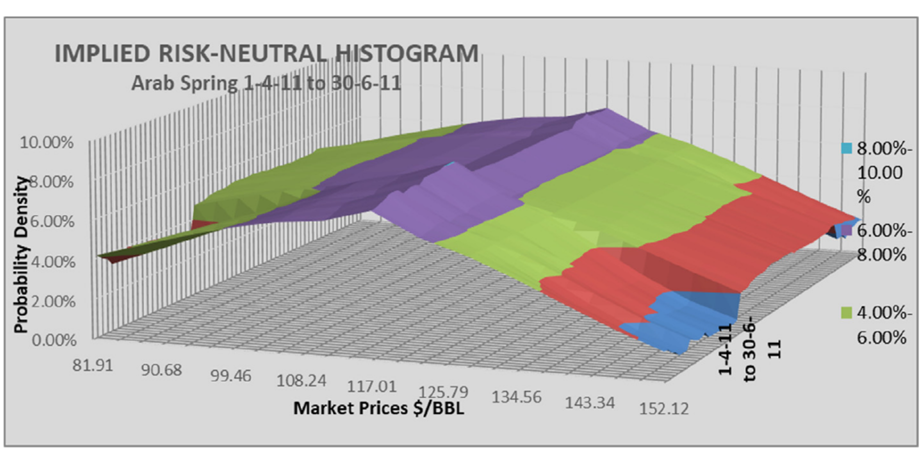

Fig. 5. Implied risk-neutral histogram for brent crude prices, Spring, 2011 (source: Authors' calculations).

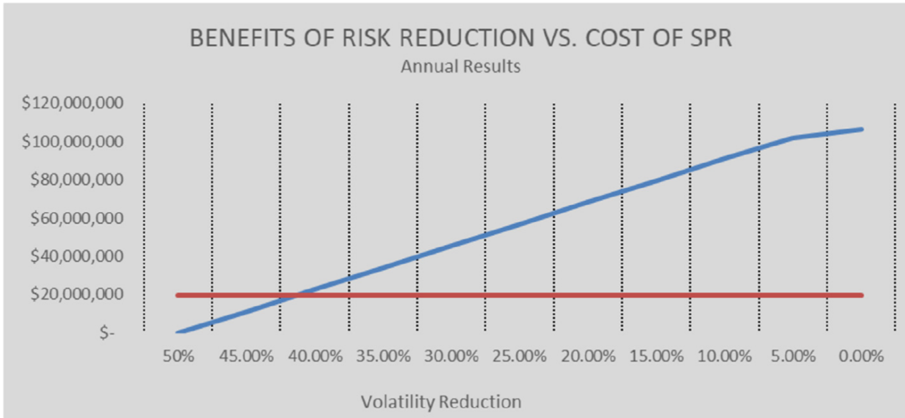

Fig. 6. The Benefits of Risk Reduction versus the Cost of the SPR. Initial volatility = 50% and length of one year. (Source: Authors' calculations).

million barrels of oil it is not optimised as a financial asset, it has an additional, indirect opportunity cost to society which should be weighed against the benefits of reducing volatility, as just explained.

Secondly, in our analysis, although we mentioned the possibility of feedback, participants discounting the probability of disruption because of the existence of strategic storage, we do not consider the potential for moral hazard in having a strategic petroleum reserve. While the existence of various reserves across the OECD might deter some exporting countries from attempting to exert market power, it might also encourage agents to not manage risks privately using derivatives or through maintaining physical storage because they know there is a supplier of last resort, as a central bank is to a banking system. This possibility has been noted in agricultural futures in the United States where despite scope for hedging of exposures, farmers prefer to rely upon price supports from the US Department of Agriculture [44].

4. Conclusions

We have reviewed the concept of energy security focusing upon the resilience or economic perspective. We have seen that there are different, valid approaches to assessing the IEA's conception of energy security as the uninterrupted availability of energy sources at an affordable price. Most approaches to measuring security embody one or more of the four criteria discussed in Section 1. Looking at long-term security, the primary focus is upon technology, investment and supply while for the short-term, the focus is upon the ability of energy systems to react promptly to sudden changes in the supply-demand balance. In the MOSES model, strategic reserves play a critical in resilience and the ability to withstand shocks but like other such work, the focus is upon the magnitude of supply disruption and the ability to mitigate the impact but not the probability of disruption. Using option theory, we have constructed forward looking risk neutral density functions on the assumption that possibility of disruptions or short-falls are embodied in how risk is priced. We argue that including market expectations of future prices, augmenting analysis using theoretical exposure, may enhance discussions of market resilience and hence energy security.

From our analysis of three interesting periods, we have seen that markets were not anticipating extreme prices as might occur under disruption. Rather according to the risk neutral density functions derived from option theory, market participants believed that shocks would be absorbed and dissipate. Although the presence of strategic reserves might have had a calming effect upon markets, we can say that without other forms of government intervention, price controls, rationing or other such mechanisms, markets equilibrated quickly and shortages did not take place. Our results suggest that discussing exposure to interruption without considering the probability of the event taking place, offers limited insight. In the insurance and financial risk management fields, loss potential or exposure embodies the physical loss, the value of such a loss, the time frame in which it may take place and *critically,* includes the probability of the event occurring. Accordingly, we argue that how energy security from an economic resilience perspective is measured warrants a re-think. Although the paucity of data for actual interruptions makes constructing probability statistics difficult, the informational embodied in option prices, in particular how the risk of extrema are priced, is a source of information on future market conditions, including market stability. According to our analysis of several important periods in international petroleum markets, the probability of disruption, as calculated from option metrics, remained small. Based upon the periods examined, the low probability given to extreme prices and disruptions, suggests that concerns over energy security, at least in the short term, may be overblown.

Given these observations, the case for maintaining strategic reserves to ensure market short-term resilience may not be strong. At least based upon the periods examined, market participants were not anticipating market dislocations and disruptions. If approximately 90 days of reserves is not necessary to ensure market resilience and long-term would be insufficient to make a difference, we considered if maintaining reserves may be justified on public good grounds of reducing market volatility? Here we found that the reduction in market volatility must be substantial in order justify the carrying plus operating costs. This result ignores the opportunity cost to society of not optimising a strategic reserve such as the Strategic Petroleum Reserve in a profit maximising manner. It also ignores the free-rider costs of sub-optimal risk management by oil companies and other interested parties in having a supplier of last resort, Government. Lastly, our results ignore the extent to which the existence of strategic reserves may have a feed-back effect, reducing short-term uncertainty. All of our results assume risk neutrality; to the extent that nations may be risk adverse, then even larger strategic reserves may be justified as insurance against disruption or to reduce price volatility. Differences between consumers versus business or between countries with regard to risk tolerance to disruption might be interesting areas for future research.

Acknowledgements

The authors wish to thank Professor Peter R. Hartley, Professor of Economics at Rice University for his helpful and insightful comments upon an earlier draft and Dr Tobias Bruenner of the University Lincoln for reviewing various calculations.

Appendix. ASupplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.esr.2019.100364.

APPENDIX. BLACK–SCHOLES EQUATION FOR EUROPEAN STYLE OPTIONS

The Black–Scholes equation is a partial differential equation, which describes the price of the option over time. The equation is:[7]

$$\frac{\partial V}{\partial t} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} + rS\frac{\partial V}{\partial S} - rV = 0$$

The Black–Scholes formula calculates the price of European put and call options. European style options may only be exercised at maturity as opposed to American style options which may be exercised any time during the life of the contract. This price, computed using the formula shown below, is consistent with the Black–Scholes equation as above since it can be obtained by solving the equation for the corresponding terminal and boundary conditions.

Thus, the formula for the value of a call option conferring the right to purchase for a non-dividend paying underlying stock in terms of the Black–Scholes parameters is:

$$C(S, T) = N(d_1)S - N(d_2)Ke^{-r(T-t)}$$

$$d_1 = \frac{1}{\sigma\sqrt{T} - t}\left[In\left(\frac{S}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)(T - t)\right]$$

$$d_2 = d_1 - \sigma\sqrt{T} - t$$

The price of a corresponding put option conferring the right to sell, based on put–call parity, is:

$$P(S, t) = Ke^{-r(T-t)} - S + C(S, t)$$

$$P(S, t) = N(-d_2)Ke^{-r(T-t)} - N(-d_1)S$$

For both equations, as above:

- *N( )* is the cumulative distribution function of the standard normal distribution
- *Tt* is the time to maturity
- *S* is the spot price of the underlying asset
- *K* is the strike price
- *r* is the risk-free rate (annual rate, expressed in terms of continuous compounding)
- *σ* is the volatility of returns of the underlying asset

Volatility is defined as the standard deviation of the return provided from holding the instrument or security for one year when the return is expressed using continuous compounding. Thus, σ^2Dt is approximately equal to the variance of the percent change in the security price in time Dt and σZDt is approximately equal to the standard deviation of the percentage change in the security price at time Dt.

References

[1] A. Cherp, J. Jewel, The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration, Environ. Sustain. 3 (2011) 1–11.

[2] Asia Pacific Energy Research Centre, A Quest for Energy Security in the 21st Century: Resources and Constraints, (2007) https://aperc.ieej.or.jp/file/2010/9/26/APERC_2007_A_Quest_for_Energy_Security.pdf.

[3] Bert Kruyt, D.P. van Vuuren, H.J.M. de Vries, H. Groenenberg, Indicators for energy security, Elsevier, Energy Policy 37 (6) (2009) 2166–2181 (June).

[4] Benjamin K. Sovacool, Marilyn A. Brown, Competing dimensions of energy security: an international perspective (November 2010), Annu. Rev. Environ. Resour. 35 (2010) 77–108 https://doi.org/10.1146/annurev-environ-042509-143035.

[5] H. Rogers, J. Stern, Challenges to JCC Pricing in Asian LNG Markets, Oxford Energy Studies, 2014 TAG NG81.

[6] M. Fygin, R. Satkin, The oil reserves to production ratio and its proper interpretation, Nat. Resour. Res. 13 (1) (2004) 57–61 March, 2004.

[7] J. Jansen, Energy services security: some metrics and policy issues, 4th Conference on Energy Economics and Technology, Dresden University of Technology, Dresden, 3 April 2009.

[8] B. Fattouh, L. Kilian, L. Mahadeva, The role of speculation in oil markets: what have we learned so far? Energy J. 34 (3) (2013) 7–33.

[9] B.W. Ang, W.L. Choong, T.S. Ng, Energy security: definitions, dimensions and indexes, Renew. Sustain. Energy Rev. 42 (2015) 1077–1093.

[10] C. Winzer, "Conceptualizing Energy Security", Electric Power Research Group Working Paper 1123, Cambridge University, 2011.

[11] D.R. Bohi, M.A. Toman, M.A. Walls, The Economics of Energy Security, Kluwer Academic Publishers, Boston, 1996.

[12] J. Jewell, The IEA Model of Short-Term Energy Security (MOSES) Primary Energy Sources and Secondary Fuels, IEA, 2011, https://www.iea.org/publications/freepublications/publication/moses_paper.pdf.

[13] F. Birol, https://www.iea.org/wei2018/.

[14] The International Energy Agency, World Energy Investment 2018, (2018).

[15] J.D. Hamilton, Historical oil shocks, in: Randall E. Parker, Robert M. Whaples (Eds.), Handbook of Economic History, Routledge, 2013.

[16] L. Kilian, Not all oil price shocks are alike: disentangling demand and supply shocks in the crude oil market, Am. Econ. Rev. 99 (1053) (2009) 1069.

[17] D. Yergin, The Prize: the Epic Quest for Oil, Money and Power, The Free Press, 1991.

[18] J.D. Hamilton, Oil and the macroeconomy since world war II, J. Political Econ. 91 (1983) 228–248.

[19] S. Ross, Options and efficiency, Q. J. Econ. 90 (1976) 75–89.

[20] D. Breeden, R. Litzenberger, Prices for state-contingent claims: some estimates and applications, J. Bus. 51 (1978) 621–651.

[21] R. Bedoui, H. Hamdi, Option-implied risk aversion estimation, J. Econ. Asymmetries 12 (2) (2015) 142–152.

[22] E.F. Fama, Efficient capital markets: a review of theory and empirical work, J. Financ. 25 (2) (1970) 383–417.

[23] K. Ladislav, M. Vosvrda, Commodity futures and market efficiency, Energy Econ. 42 (2014) 50–57 https://www.iea.org/publications/freepublications/publication/the-iea-model-of-short-term-energysecurity.html https://www.iea.org/media/.../EnergySupplySecurity2014_PART1.pdf ENERGY SUPPLY SECURITY 201.

[24] Y. Wang, L. Liu, Is WTI crude oil market becoming weakly efficient over time? New evidence from multiscale analysis based on detrended fluctuation analysis", Energy Econ. 32 (5) (2010) 987–992.

[25] P. Leiby, D. Bowman, "Economic Benefits of Expanded Strategic Petroleum Reserve Size or Drawdown Capability," December 31, Final Report, Oak Ridge National Laboratory, 2006 ORNL/TM-2006/5.

[26] J.C. Jackwerth, M. Rubenstein, Recovering probability distributions from option prices, J. Financ. 51 (1996) 1611–1631.

[27] M. Rubenstein, Nonparametric tests of alternative option pricing models using all reported trades and quotes, J. Financ. 40 (1985) 455–480.

[7] As covered in Ref. [49]; Chapter 15.

[28] J. Jackwerth, Recovering risk aversion from option prices and realized returns, Rev. Financ. Stud. 13 (2) (2000) 433–451.
[29] S.J. Taylor, Asset Price Dynamics, Volatility and Prediction, Princeton University Press, 2007.
[30] R. Bliss, N. Panigirtzoglou, Testing the stability of implied probability density functions, J. Bank. Financ. 26 (2–3) (2002) 381–422.
[31] R. Bliss, N. Panigirtzoglou, Option-implied risk aversion estimates, J. Financ. LIX (1) (2004) 407–446.
[32] W.R. Melick, C.P. Thomas, "Recovering an asset's implied PDF from option prices: an application to crude oil during the Gulf crisis", J. Financ. Quant. Anal. (1997) 91–115.
[33] Y. Ait-Sahalia, A. Lo, Nonparametric Estimation of State-Price Densities Implicit in Financial Asset Prices, (1995) NBER, working paper No. 5351.
[34] U.S. Department of Energy Websites Consulted, https://energy.gov/fe/services/petroleum-reserves/strategic-petroleum-reserve/releasing-oil-spr https://www.eia.gov/naturalgas/storagecapacity/https://www.eia.gov/dnav/pet/pet_stoc_typ_d_nus_SAS_mbbl_m.htm https://www.theice.com/products/Futures-Options/Energy http://www.iea.org/publications/freepublications/publication/GasResiliencyAssessmentofJapan.pdf https://www.iea.org/publications/freepublications/publication/GlobalGasSecurityReview2017.pdf http://shareholdersunite.com/the-ioc-files-useful-background-material/the-economics-of-lng/https://bluegoldresearch.com/global-lng-prices https://www.downsizinggovernment.org/agriculture/subsidies.
[35] P. Lee, IMPACT of the GULF WAR: Crude Plunges; Gasoline Prices to Dealers Cut: Energy: the Movement Defies Predictions. But Analysts Warn that Negative News Could Quickly Reverse the Market's Course, Los Angeles Times, 18-1-1991, http://articles.latimes.com/1991-0118/business/fi-102_1_oil-prices.
[36] E. Santi, S.B. Romdhane, Mohamed Safouane Ben Aïssa, "Impact of Libya's Conflict on the Tunisian Economy: A Preliminary Assessment", North Africa Quarterly Analytical, African Development Bank, 2011, pp. 1–16.
[37] Financial Times, https://www.ft.com/content/6e91d54e-00e7-11e3-891800144feab7de, (9-8-2013).
[38] Financial Times, https://www.ft.com/content/f679b6a0-9dae-11e0-b30c00144feabdc0, (23-26-2011).
[39] H. Darbouche, B. Fattouh, The Implications of the Arab Uprising for Oil & Gas Markets, Oxford Institute for Energy Studies, MEP2, 2011.
[40] P. Stevens, The Arab Uprising and the International Oil Market, Chatham House – EERG, 2012, https://www.chathamhouse.org/sites/files/chathamhouse/public/Research/Energy%2C%20Environ ment%20and%20Development/bp0212stevens.pdf.
[41] H. Hotelling, The economics of exhaustible resources, J. Political Econ. 39 (2) (1931) 137–175.
[42] P.S. Dasgupta, G.M. Heal, J. Nisbet, Economic Theory and Exhaustible Resources, Cambridge University Press, Cambridge, UK, 1979.
[43] B.E. Kirwan, The incidence of U.S. Agricultural subsidies on farmland rental rates, J. Political Econ. 117 (1) (2009) 138–164 University of Chicago Press.
[44] Brian M. Riedl, Farm Subsidies Are Ripe for Reform, The Heritage Foundation, 2011, http://www.heritage.org/social-security/commentary/farm-subsidies-are-ripe-reform.
[45] P.A. Samuelson, The Pure Theory of Public Expenditure, Rev. Econ. Stat. (1954) 387–389.
[46] L. Clewlow, C. Strickland, Energy Derivatives: Pricing and Risk Management, Lacima Publications, London, 2000.
[47] H. Geman, Risk Management in Commodity Markets: from Shipping to Agriculturals and Energy, Wiley Finance, 2008.
[48] P.C. Beccue, H.G. Huntington, "An Updated Assessment of Oil Market Disruption Risks", FINAL REPORT EMF SR 1, FINAL REPORT EMF SR 10 Energy Modelling Forum Stanford University Stanford, CA 94305-4121 Prepared for the Office of Petroleum Reserves U.S. Department of Energy Washington, D.C, (2016), p. 20036.
[49] J.C. Hull, Options, Futures and Other Derivatives, sixth ed., Prentice Hall, 2006.
[50] European Union Commission, COMMUNICATION from the COMMISSION to the EUROPEAN PARLIAMENT and the COUNCIL on European Energy Security Strategy, /* COM/2014/0330 final */" https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/energy-security-strategy.