INTERNATIONAL ENERGY AGENCY

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Costs and benefits of emergency stockholding

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Acknowledgements

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PJK International B.V. undertook the update of the costs involved in holding emergency oil stocks. For this work, PJK provided advisory services about tank storage facilities. Recent data were obtained from interviews with stockholding agencies, operators of aboveground and underground facilities, construction companies and terminal operators.

The ORNL Energy Analysis Team has been studying energy security, oil shocks and emergency oil reserves for over 25 years. The team developed a sophisticated model, BenEStock, to simulate oil supply disruptions and their economic impacts. For this study, the team developed supply disruption simulations to assess stockholding benefits, accounting for changes in current and projected oil market conditions over the next 30 years; the research team was led by Mr. Paul Leiby.

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Executive summary

In 2013, the IEA published a first study on the costs and benefits of holding emergency oil stocks to provide guidance to countries considering the creation of a new stockholding system or expanding their existing system. The study drew together estimates of both the costs and the benefits of holding emergency oil stocks, in addition to exploring options for financing the establishment of stocks. Since the original study was published, significant developments have occurred in global energy markets, such as volatility in crude and oil product prices and changes in the production profile of the USA. Oil continues to be traded in a market where uncertainty and sudden supply shocks are common occurrences.

In order to assess the net benefits derived from holding emergency oil stocks under current market conditions, an update of the study has been undertaken. The update, presented in this report, quantifies the costs involved in holding emergency stocks, accounting for the 2017/18 market conditions, before assessing the benefits associated with holding these stocks.

Following the approach in the first study, this update is based on three assumptions:

- Stockholding costs include the construction costs of the storage facilities, the maintenance costs of these facilities, the expenditures for purchasing the crude oil and products, and the operational costs of running the stockholding system.
- Costs refer to public oil stocks held exclusively for emergency situations.
- The model takes into account global crude oil disruptions to assess the benefits of emergency stocks.

In this report, "hard to quantify" benefits such as foreign policy and national security benefits, as well as benefits during domestic supply shocks or disruptions, are not included. The estimated costs and benefits covered in the report indicate an order of magnitude at the global and regional levels.

Due to a sharp decrease in crude and oil product prices since the time of the first study, the overall costs of holding emergency stocks have dropped substantially, overshadowing the impact of changes in any of the other cost categories. The 2018 updated costs for the storage of emergency stocks, including the cost of purchasing the liquid fuels, have decreased for all storage types; underground storages (in rock caverns or salt caverns) remain cheaper compared with above-ground storages. The estimated stockholding costs are in the range of 7 US dollars (USD) to USD 8.60 per barrel of oil per year for a storage facility (with a total capacity of at least 500 000 cubic metres [m^3]) using a 3% discount rate (base case assumptions). With a 7% discount rate, the estimated stockholding costs increase compared to costs calculated with the base case assumptions, ranging from USD 10 to USD 12.40 per barrel of oil per year.

Economic benefits consist of avoided losses in gross domestic product (GDP) and reduced import costs. The economic benefits of emergency oil stocks follow from their ability to restore oil supply during disruptions and thereby dampen oil price increases. Preventing price increases avoids substantial import costs and GDP losses. Historical experience suggests that supply disruptions will recur in the oil market. However, the specific magnitude, timing and consequences of future supply losses remain uncertain. To account for this uncertainty, the benefits of emergency stocks were examined by a randomised model that simulates the global economic benefits of IEA emergency oil stocks over thousands of possible future disruptions and market outcomes over a time horizon of 30 years. Each outcome is weighted by its assessed likelihood.

Under the base case assumptions in this report, the total expected benefits of IEA stocks to all global importing regions is about USD 60 per barrel per year. Accumulated over 30 years, the total benefits are USD 3.9 trillion.[1] This estimate is based on benefits to all countries that are net importers of oil. This value is an average payoff from the "insurance" provided by stocks, though the actual benefits would depend on the particular oil market future ultimately realised.

In this analysis, the benefits derived from IEA emergency stocks for the non-IEA importing countries are higher than the benefits to the IEA member countries. The principal reason for this is that non-IEA oil consumption and GDP are projected to grow significantly over the 30-year horizon of the simulation, eventually exceeding collective consumption and GDP of IEA member countries. The higher share of non-IEA countries in global oil consumption and global GDP is reflected in a higher share of the benefits for these countries derived from stocks during a supply disruption. Thus, while becoming more vulnerable to global oil supply disruptions, the greater share in oil consumption and GDP of these countries is reflected in a high share of the benefits derived from the release of emergency stocks. In contrast, most IEA countries are reducing oil demand through vehicle efficiency and fuel diversification, which works to reduce the sensitivity of their economies to oil market changes, consequently reducing the amount of GDP loss that is avoided (i.e. the benefit) from the emergency stock release.

In this updated study, net benefits are about 10% higher on a basis of USD per barrel of oil per year compared with the 2013 estimates. One reason for this increase is that there are fewer barrels of IEA emergency stocks in the projected future, given planned sales by the US Strategic Petroleum Reserve (SPR) and reductions in consumption or import levels in some IEA countries. There are other factors at work, however, in offsetting directions. For example, a survey of recent empirical estimates suggests a lower average sensitivity of global economies to oil price shocks than previously estimated, while oil demand is now estimated to be less flexible in the short run, making it less able to accommodate supply shocks without significant price increases.

[1] In this report, whenever a measure of benefits is cumulated or averaged over multiple years, the values over time are "discounted" or adjusted by an annual discount rate.

1. Introduction – The need for emergency oil stocks

Oil markets have experienced many supply disruptions since the IEA started co-ordinating oil stockholdings among its members in the early 1970s. On three occasions since 1990, co-ordinated, multilateral stock releases occurred, and their contribution to helping the market adjust was evident. Even when stock releases did not occur during some market events, the availability of emergency stocks might have helped prevent panic reactions by market participants and reduced economic damage.

This report looks ahead at the next 30 years and evaluates the expected economic benefits of emergency oil stockholding. It closely follows the approach of a first study of this kind,[2] completed in 2013. It intends to serve as a resource for IEA member countries, IEA accession and IEA association countries, and any other country interested in designing and implementing emergency oil stocks. As the results of this work have a global perspective, it is important for individual countries to conduct their own analyses, reflecting their national circumstances.

This study addresses the implications of many developments within the oil market by updating projected oil market conditions, estimates of disruption risks and selected economic assumptions. It also presents the updated cost items for public oil stocks held exclusively for emergency situations and stored in newly built facilities. The cost update assessment does not include historical costs; many of the facilities in IEA countries were constructed and filled at times when prices were very different from today.

This study calculates the collective global benefits of existing IEA stocks, counting benefits to all countries that are net oil importers, not just IEA countries. Economic benefits are calculated as the expected reduction in disruption costs compared with a situation where no stocks are made available. The report also briefly discusses additional benefits of stocks that are difficult to quantify, non-economic or specific to a particular country that is holding the stocks.

1.1 Implications of oil supply disruptions

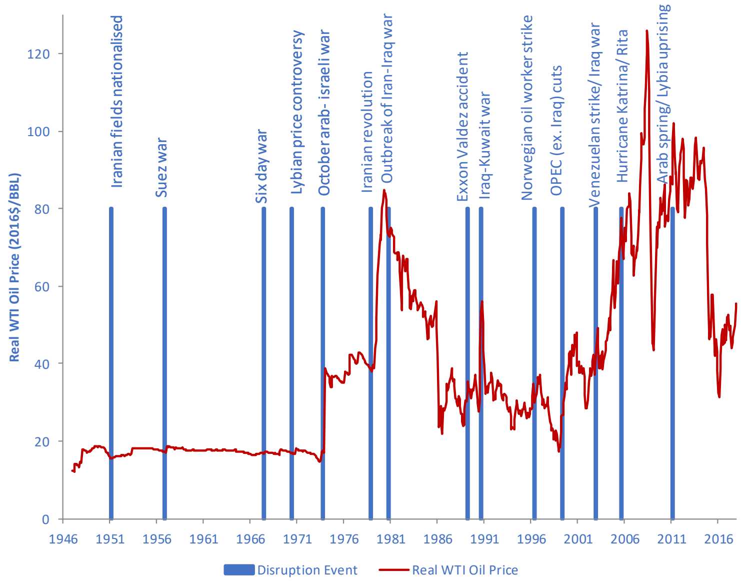
Accidents, natural disasters, strikes and geopolitical conflicts have resulted in dozens of events over the last decades in which global oil supply was abruptly reduced. Figure 1 presents a timeline that combines the trajectory of monthly real oil price (in 2016 US dollars) with major oil disruption events that generally produced average gross supply losses of 1 million barrels of oil per day (mb/d) or greater. Almost all of the large supply disruptions included in this timeline resulted in price increases.

For a commodity as vital to the global economy as oil, and whose demand is highly inelastic in the short run, price increases due to sudden supply losses can be very large. For some of the disruptions illustrated in Figure 1 (Arab-Israeli War, Iranian Revolution, Iraq-Kuwait War, production cuts from the Organization of the Petroleum Exporting Countries [OPEC]), the associated prices approximately doubled relative to pre-disruption levels. The potentially large oil price increases that follow a supply disruption can impact the world economy through multiple channels, including inflationary pressures, reductions in capacity utilisation rates and dislocations in labour markets. These impacts ultimately translate into reductions in the economic performance of net-oil-importing countries, summarised by changes in the GDP, and significant

[2] www.iea.org/publications/insights/insightpublications/FocusOnEnergySecurity_FINAL.pdf.

wealth transfers to oil-exporting countries. If the disruption is large enough to trigger a global recession, even producing countries can be impacted.

Figure 1 • Real West Texas Intermediate (WTI) price and selected historical world oil supply disruptions



1.2 Future oil market risks

Over the next decades, the world will continue to be exposed, possibly even more than in the past, to significant oil supply risks. Those risks could be geopolitical conflicts, weather-related events (hurricane, earthquake), logistics disruptions at critical choke points or cyberattacks. For the purposes of the model, five "at risk" regions are defined: Saudi Arabia, Other Persian Gulf,[3] Africa,[4] Latin America[5] and Russia and Caspian Region[6]). The contribution from these regions to total world supply has steadily increased over the last two decades and is expected to continue to increase in the coming decades, despite the large increase in US production.

Most of the projected increase of at-risk production is in Persian Gulf countries, the region from which the largest historical oil supply disruptions have originated. Supply from the other at- risk regions make up the remaining at-risk production capacity. After a large oil supply disruption in one region, spare production capacity[7] in other regions is valuable to offset part of or the entire deficit in the global market. Most of the production capacity that meets these requirements is located in OPEC countries, particularly in Saudi Arabia. Figure 3 shows historical and projected volumes of spare capacity in OPEC countries.

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[3] In this report, Other Persian Gulf includes Iran, Iraq, Kuwait, Qatar, United Arab Emirates and Oman.

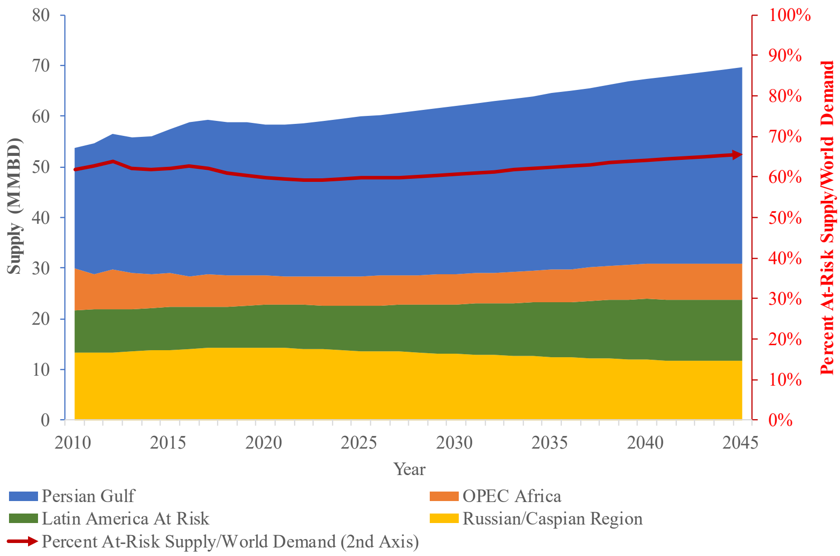
[4] In this report, Africa refers to OPEC Africa: Algeria, Angola, Libya and Nigeria.

[5] In this report, Latin America refers to Brazil, Mexico and Venezuela.

[6] In this report, Russia and Caspian Region refers to Azerbaijan, Kazakhstan, the Russian Federation (hereafter, "Russia"), Turkmenistan and Uzbekistan.

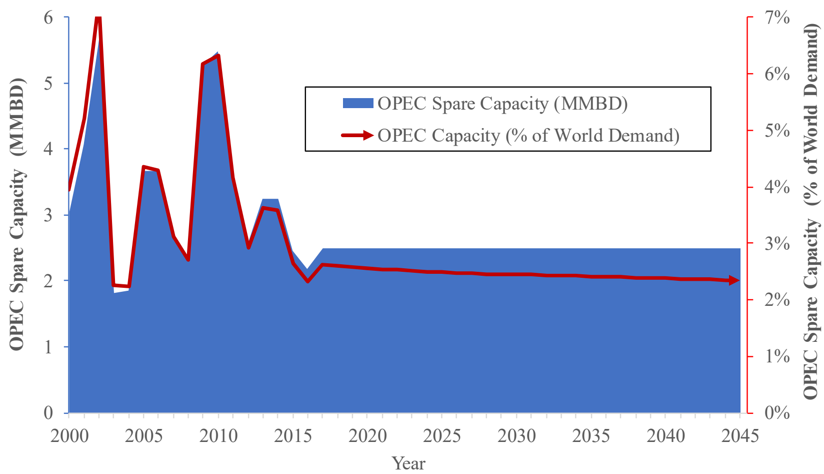
[7] The IEA defines spare capacity as "the capacity levels that can be reached within 30 days and sustained for at least 90 days."

Figure 2 • Projected growth of production from regions with high geopolitical risk



Spare capacity has fluctuated over the past decades, driven by alternating periods of rapid macroeconomic growth and recessions. In particular, rapid growth of the global economy from 2003 to 2007 and the emergence of new large energy consumers, such as the People's Republic of China (hereafter, "China"), India and Brazil, followed by a deep recession in 2008 and 2009, saw OPEC spare capacity decline from about 6 mb/d in 2002 to about 3 mb/d in 2014. Most of the current spare capacity of about 2.5 mb/d is located in Saudi Arabia. To take into account uncertainties about spare capacity, a sensitivity analysis was done with a low case scenario (1 mb/d) and a high case scenario (3 mb/d) for spare capacity. Total OPEC spare capacity is currently about 3% of total world demand, very far from the 15% values observed in the early 1980s.

Figure 3 • OPEC spare capacity levels and as fraction of world demand



The IEA and the US Energy Information Administration (EIA) both project a future of low spare oil production capacity. Thus, OPEC spare capacity would represent a decreasing fraction of global world demand over the medium to long run, greatly increasing the probability that emergency stock releases would be needed to respond to future supply disruptions. US tight oil production is more flexible than conventional oil production in IEA countries, but it does not have the same flexibility as OPEC spare capacity. Moreover, the US tight oil production is a limited fraction of global oil supply of about 5% (5 mb/d) in 2018 and projected to grow to 7% (nearly 8 mb/d) by 2030, so any rapid increase would only be in limited quantities.

1.3 Emergency stocks to address growing oil supply risk

Oil emergency stocks are a valuable tool for reducing losses from supply shocks. To maximise their effectiveness, multinational co-ordination of planning and release decisions are essential. It is in this spirit that IEA members maintain petroleum emergency stocks and that the IEA has launched collective actions on three occasions – during the first Gulf War in 1991, after Hurricane Katrina in 2005 and during the 2011 Libyan civil war. The long history of oil supply disruptions and likely higher future risks create concerns about the economic impacts of such disruptions on oil-importing economies. Under these conditions, the prospective need for and value of buffer stocks is notably greater. In that context, this study evaluates the future benefits of IEA emergency oil stocks.

2. Costs of holding emergency oil stocks – update with 2017/18 market conditions

2.1 Methodology of the cost update

This chapter presents the results of a study by PJK International B.V. commissioned by the IEA. The study focuses on updated cost items for public oil stocks held exclusively for emergency situations and stored in newly built facilities. The cost update assessment does not include historical costs, as many of the facilities in IEA countries were constructed and filled at times when prices were very different from today.

Updating the costs of holding emergency oil stocks in IEA member countries on a comparable basis poses certain challenges. Difficulties arise from the lack of sufficient data for some regions, varying coverage of costs (e.g. inclusion or exclusion of costs of land acquisition, oil acquisition), local scarcity of steel and so forth. As a result, the updated cost estimates are presented at a global level. The costs considered in this report consist of the construction costs of the storage facilities, the maintenance costs of these facilities, the expenditures for purchasing the crude oil and products, and the operational costs of running the storage facilities. The cost estimation has been calculated with the parametric cost model for the 2013 study. The different cost items are listed in Table 1.

Table 1 • Cost items for the cost estimates

Cost category	Cost items
General	Project lifetime of terminal, depreciation period of terminal, remaining value of terminal after project lifetime, inflation, real discount rate, US dollar/euro (EUR) exchange rate.
Investments	Average total capacity of terminal, investment in tank per cubic metre capacity, price of steel for tank construction, investment in jetty, land-side loading/unloading, land utilisation in cubic metre tank capacity per square metre (m^2) of land.
Annual expenses	Land lease expense,operating expense, corporate tax.
Refreshment of oil stocks	Duration of refreshment exercise, ageing fee/shipping fee, cost of alternative storage during refreshment, terminal handling cost.
Stock composition	Product share in relation to total obligation, crude price, product price, average product density.

The cost update was done in two phases:

- Re-evaluation of all cost items that were used in the 2013 study with special attention to the items with a significant influence on overall costs, and cost items that have changed materially since 2012.
- Assessment of the impact of each cost item on the cost level of holding emergency stocks.

The costs are assessed for different types of storage facilities (i.e. above-ground tanks and underground caverns) as well as for different compositions of stocks (crude/product). The cost information in this report is provided in US dollars per barrel (USD/bbl) per year.

In order to evaluate the sensitivity with respect to the end results, the updated parameters have been inserted individually or in combination depending on the cost item. For instance, oil price and product price have been inserted together in the model since they are linked to each other. Some parameters are defined in ranges to cover the variety of the cost levels encountered in the different countries/regions.

The costs of holding strategic stocks are heavily influenced by the cost of capital. For this update, the real discount rates are 3% and 7%; the lower level reflects the favourable credit ratings granted to governments and public stockholding entities, while the higher level is relevant for commercial loans.

For the cost update, the important parameters are listed in Table 2, and the full list of parameters and assumptions is presented in Annex D. The value of some parameters have significantly changed since 2012, and they have been updated after consultation with the SEQ delegates.

Table 2 • Updated parameters for the cost estimation

Parameter	Value (2018 study)
Inflation	2% per year
Rate of exchange (USD to EUR)	1.174
Real discount rate (base case)	3%
Real discount rate (sensitivity case)	7%
Steel price	EUR 1 450 per million tonnes (Mt)-EUR 1 650/Mt
Land lease expenses	EUR 7.40/m² per year
Operating expenses	EUR 10/m³-EUR 12.50/m³ per year
Corporate tax	24%
Cost of alternative storage during refreshment	EUR 18/m³-EUR 22.50/m³ per year
Crude price	USD 59.37 per barrel (bbl)
Product price	USD 577/Mt
Range of commercial storage rates (above-ground tanks)	EUR 20/m³-EUR 24/m³ per year
Range of commercial storage rates (caverns)	EUR 7/m³-EUR 12/m³ per year

Inflation: The inflation rate is in agreement with the monetary policies currently pursued by the European Central Bank (ECB)[8] and US Federal Reserve[9]. The long-term inflation target is formulated as being “below but close to 2% per year”.

Rate of exchange: The exchange rate has been updated and set at USD 1.174 for EUR 1.

Real discount rate: The discount rate depends on many factors, including source of funds, affected stakeholders and level of risk. For public assets, such as emergency stocks, it is often assumed to be the risk-free interest rate on government funds. The costs have been estimated based on a 3% real discount rate for the base case. Since alternative discount rates for public assets may apply, this situation is reflected in the sensitivity case by using a 7% real discount rate.

Steel price: The steel price has been rising in Europe and is expected to continue to rise (25-30%) in the foreseeable future due to anti-dumping import restrictions and import levies imposed on steel manufactured in China. The high level of the current all-in steel price at EUR 1 650/Mt was used with a location factor of +/- EUR 200/Mt to reflect lower-cost regions.

[8] www.ecb.europa.eu/mopo/strategy/pricestab/html/index.en.html.

[9] www.federalreserve.gov/newsevents/testimony/yellen20170214a.htm.

Land lease expenses: The land lease cost is based on the assumption that sites used for strategic storage operations are preferably along deep water in deep sea ports. Sites farther away from deep water carry lower "long lease" cost.

Operating expenses: Given the prolonged period of storage, it is relevant to choose a range of EUR 10/m^3-EUR 12.50/m^3 per year to cover for possible price rises in the future. However, operational costs in low-cost countries will remain at the lower limit of the range.

Corporate tax: For the 2017/18 study, the Organisation for Economic Co-operation and Development (OECD) corporate tax rate[10] as calculated by KPMG has been selected.

Cost of alternative storage during refreshment: It is assumed that refreshment is covered by tickets, and not by renting additional storage capacity. This may not necessarily be the case in smaller tank storage markets. Based on historic weighted average ticket prices since 2013, the costs of alternative storage during refreshment is between EUR 18/m^3 and EUR 22.50/m^3 per year, depending on the product and storage types.

Crude price: The crude oil price is based on forward settlement prices for Brent, Forties, Oseberg and Ekofisk (BFOE) crude ("Brent crude") traded on the Intercontinental Exchange (ICE) Europe on 2 January 2018 (source Thomson Reuters).

Product price: The petroleum product price is based on forward settlement prices for ultra-low sulphur diesel and on closing prices for gasoline swaps (source Thomson Reuters) traded on 2 January 2018. Based on the current OECD split in oil product inventories (80% diesel/20% gasoline), a weighted average between diesel and gasoline was used.

Range of commercial storage rates (above-ground tanks): Tank storage rates vary significantly around the world due to market size, competition and location in relation to supply/demand. Tank storage rates have recovered from the economic downturn in 2012. For above-ground tanks for storage, the costs are EUR 20/m^3-EUR 24/m^3 per year.

Range of commercial storage rates (caverns): The costs vary between EUR 7/m^3 and EUR 12/m^3 per year, which includes the consideration that the average fee for cavern storage in the United States is about half of the European fee, which varies between EUR 9/m^3 and EUR 14/m^3 per year.

2.2 Market context for the global tank storage capacity

The global land-based tank storage capacity (captive[11]/dedicated, independent and hybrid capacity), is estimated at 3 billion m^3 to 3.5 billion m^3. Dedicated capacity is largely owned and operated by refineries and upstream oil companies; about 75% of the total global capacity is estimated to be captive.

The global independent tank storage capacity is estimated at 600 million m^3 to 700 million m^3 (about 20% of total, depots excluded) and growing (about +25% in the last five years). Well-known operators are Vopak, Oiltanking, Kinder Morgan, Sinopec, etc. There are about 1 000 independent operators globally with about 4 500 terminal facilities. This market has become of interest to private equity players (e.g. KKR, Macquarie, First Reserve) and pension funds due to their appealing risk/return balance. The independent tank storage market is highly

[10] https://home.kpmg.com/xx/en/home/services/tax/tax-tools-and-resources/tax-rates-online/corporate-tax-rates-table.html.

[11] Producers and traders using their capacity only for storing their own products.

fragmented. The largest independent operators do not control more than 5% of the total global independent tank storage market. The impact of the independent tank storage industry on oil product pricing is significant. The reasons are the strategically chosen locations, the extensiveness of their hub and spoke terminal network,[12] the operational flexibility and diversity, and their commercial acumen.

The emergence of tank storage brokers and platforms makes the independent tank storage market more transparent. The overriding characteristic of the independent tank storage industry is that these owners-operators never own any of the products they store; they are the custodians of the products for the period of storage.

Hybrid operators are tank terminals owned or operated by companies that own quantities of products during parts of the value chain, from source to destination. Hybrid operators might store products in their own facilities. Hybrid capacity is, for instance, owned-operated by global oil traders, e.g. Vitol (VTTI), Mercuria (Vesta), Gunvor, Trafigura (Puma). Hybrid capacity also includes refinery capacity that is leased out commercially from time to time. The hybrid capacity is small and far smaller than the total independent capacity, but growing significantly in the recent years.

2.3 Core figures for oil storage

An indication of the investment level for building above-ground storage tanks for oil products at a new facility is about EUR 110/m^3 to EUR 150/m^3, excluding jetty infrastructure.

Comparison and differentials between above-ground tank storage and underground cavern storage:

2.3.1 Investments

- Investment in above-ground tank storage, new facility: EUR 110/m^3-EUR 150/m^3
- Investment in above-ground tank storage, add-on facility: EUR 90/m^3-EUR 130/m^3
- Investment in underground cavern storage, salt caverns: EUR 40/m^3-EUR 50/m^3
- Investment in underground cavern storage, rock caverns: EUR 400/m^3-EUR 650/m^3 and up for purposely built concrete caverns.

The investment cost has increased up to 10% since 2012, due to more stringent health, safety, security and environment (HSSE) specifications (double containment or double-walled pipeline) and higher utilities costs.

2.3.2 Range of storage renting rates for strategic storage purposes

- Average rate for above-ground tank storage, new facility: EUR 20/m^3-EUR 24/m^3 per year
- Average rate for above-ground tank storage, add-on facility: EUR 20/m^3-EUR 24/m^3 per year
- Average rate for underground cavern storage, salt/rock caverns: EUR 7/m^3-EUR 12/m^3 per year.

[12] Spoke terminal refers to small terminal facilities.

2.3.3 Range of commercial tank storage renting rates

- Average rate for above-ground tank storage, indicative: EUR 36/m³-EUR 50 /m³ per year
- Above-ground storage tank rates are affected by competition, geographical differences, contango-backwardation, parcel size, tank size, throughput, mode in/mode out, duration of contract and political unrest.

In addition to the costs mentioned before, the ageing and shipping fees are included in the cost estimates, and they vary depending on the product categories, storage locations and market situation. In the cost model, this report assumed the following refreshment periods: 20 years for crude oil and 6 years for refined products.

For products stored in terminals connected to distribution infrastructure such as pipelines/rail/barge, a buyer would have a low level of additional costs. For this situation, the ageing and shipping fees are set at USD 4/Mt for the cost estimate, similar to the 2012 value.

For remote storage terminals, additional transport costs apply depending on the specific location and loading/discharging infrastructure. Assuming that the terminal has sea access and can handle standard vessels, the additional costs would be around USD 15/Mt.

2.4 Storage costs for 2017 and 2018

Due to a sharp decrease in the crude and oil product prices since 2012 (more than 50% for crude, and around 40% for oil products), the overall cost of holding emergency stocks has dropped notably, overriding the impact of the increase of any other cost items. The 2018 updated costs for emergency stock storage, including the cost of oil stock, have decreased for all the storage types; underground storage (in rock caverns or salt caverns) remain cheaper for stockholding compared with above-ground storage. The difference between stockholding costs in salt caverns and stand-alone facilities is nearly 20%.

The results for the updated costs are shown in Table 3.

Table 3 • Updated costs for emergency stockholding

Storage types	2018 costs (USD/bbl per year) (3% real discount rate – base case)	2018 costs (USD/bbl per year) (7% real discount rate)
Above-ground storage		
Stand-alone facility	8.58	12.38
Add-on facility	8.35	12.02
Underground storage		
Salt cavern	7.02	10.04
Rock cavern	8.16	11.75

The estimated stockholding costs range from USD 7/bbl to USD 8.60/bbl per year with a 3% discount rate (base case). With a 7% discount rate, the estimated stockholding costs are higher compared with the ones calculated with the base case assumptions, and they range from USD 10/bbl to USD 12.40/bbl per year depending on the storage type. For above-ground storage, the results presented above are for a 500 000 m³ terminal; for a smaller stand-alone tank of 100 000 m³, the same trend is observed with regard to reduction of the yearly stockholding costs.

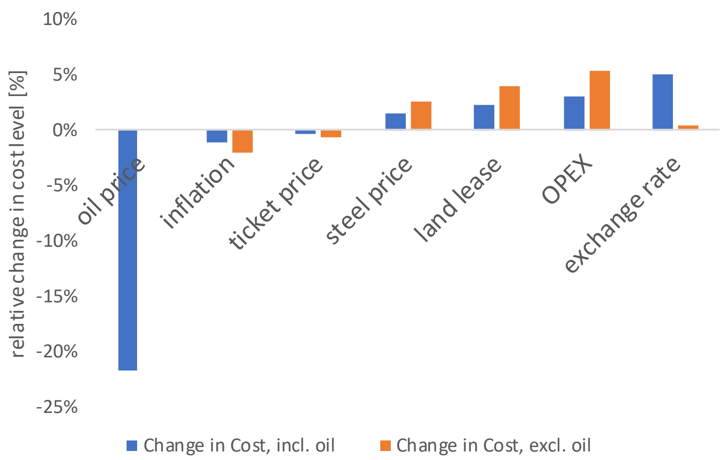
The overall cost level of holding strategic stocks is impacted by including or excluding the cost of buying oil.[13] In the case of a 500 000 m³ terminal, the capital expenditure (CAPEX) to build the storage tanks is approximately EUR 50 million. The cost of 500 000 m³ of petroleum products (with the ratio of 70% crude and 30% products) is approximately EUR 200 million, roughly four times the value of the terminal's hardware. A change in crude/product price has a four-time larger effect on the overall cost than a change in the price of the elements used to build the storage facility (e.g. steel).

If using USD 15/Mt instead of USD 4/Mt for the ageing/shipping fee, this would translate into an additional cost of approximately USD 0.10/bbl per year for the base case assumption with a stock composition based on 70% crude oil and 30% products.

The variation of the exchange rate between the US dollar and the local currency used at the storage location has a significant effect on the overall investment and consequently the cost level. Crude and oil product prices are stated in US dollars, and a large portion of the overall investment amount is stated in the local currency where the storage facility is built.

Figure 4 presents the changes in 2018 versus 2012 cost levels.

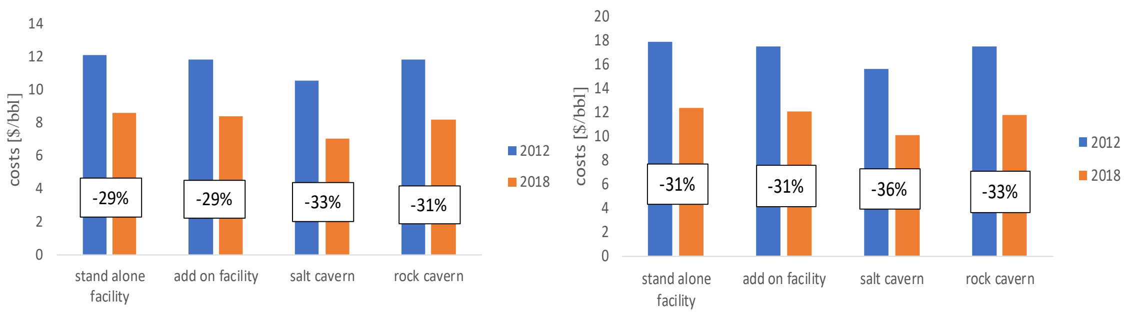
Figure 4 • Relative changes in oil storage costs (2018 versus 2012 cost levels)



If the drop in oil prices is included in the cost calculation, the total cost level has decreased across all storage terminal types, above-ground and underground, compared with the previous study. The cost levels increase with a higher interest rate (7%) applied. The comparisons are shown in Figure 5.

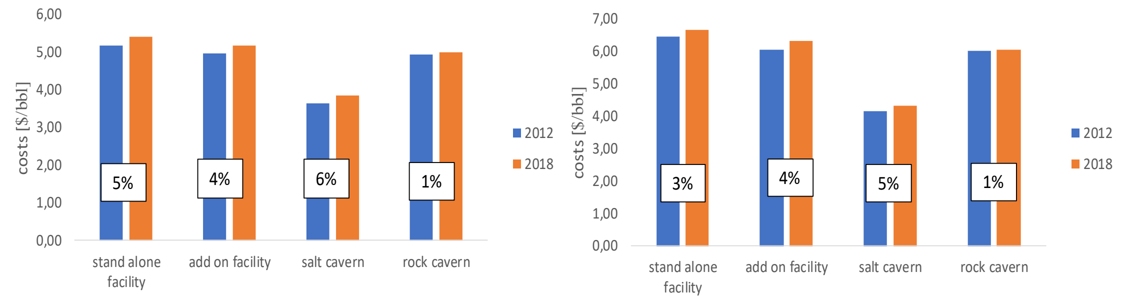
[13] The 2013 study outlined the purchase price of the crude oil and/or oil products to be a major part (up to 80%) of the total required investment costs as well as a very significant factor (50-85%) in the resulting annual charges of holding strategic oil stocks.

Figure 5 • Storage costs (USD/bbl per year) with 3% and 7% real discount rates, including oil cost



If the impact of the change in oil prices is excluded from the calculation, the total costs have increased by 1% to 6% depending on the storage type. Due to the introduction of more stringent HSSE regulations to protect the environment against leakage and spillage, the operating expense (OPEX) for storage has increased by about 2%. The steel price and land lease costs have the largest effects on the storage costs. The increased steel price has pushed up the overall cost for storage in above-ground tanks by about 11%. The investment costs for building caverns have increased by up to 10% due to higher power costs. The results are presented in Figure 6.

Figure 6 • Storage costs (USD/bbl per year) with 3% and 7% real discount rates, excluding oil cost



2.5 Conclusions – main changes in cost levels

Due to a sharp decrease in crude and oil product prices since 2012, the overall costs of holding emergency stocks have dropped notably, overshadowing the impact of other cost items. The 2018 updated costs for emergency storage, including the cost of oil stock, have decreased for all the storage types by approximately 30%; underground storage (in rock caverns or salt caverns) remains about 20% cheaper for stockholding compared with above-ground storages.

The estimated stockholding costs range from USD 7/bbl to USD 8.60/bbl per year with a 3% discount rate (base case). With a 7% discount rate, the estimated stockholding costs increased compared with the ones calculated with the base case assumptions, and they range from USD 10/bbl to USD 12.40/bbl per year.

If the impact of the change in oil price is excluded from the calculation, the total costs have increased by 1% to 6% depending on the storage type. Due to the introduction of more stringent HSSE regulations to protect the environment against leakage and spillage, the OPEX for storage has increased by about 2%. The steel price and land lease costs have the largest effects on the above-ground storage costs; the increased steel price has pushed up the overall cost by about 11%. The investment costs for building caverns have increased by up to 10% due to higher power costs.

3. Results of the economic benefits analysis

This chapter presents the results of a study by ORNL, commissioned by the IEA. This section describes the collective global benefits of existing IEA emergency oil stocks, counting benefits to not only IEA member countries but also to net oil importers that are not members of the IEA. Economic benefits are calculated as the expected reduction in disruption costs compared with a situation where no emergency oil stocks are made available. The chapter also briefly discusses additional benefits of emergency stocks that are difficult to quantify, non-economic or specific to a particular country that is holding the stocks.

Oil supply disruptions are simulated against reference paths for oil prices and oil supply and demand for four world regions (IEA North America, IEA Asia and Pacific, IEA Europe, and non-IEA net importing countries). Reference oil market paths track the New Policies Scenario of the IEA *World Energy Outlook 2017* (*WEO 2017*). BenEStock computes the benefits from using emergency stocks in cases of disruptions as well as stock level, stock use, net oil costs, and other relevant variables. Disruption impacts are modelled on a monthly basis, for up to 36 months in length, over the period from 2018 to 2047 (30 years).

The six key inputs for estimating the strategic economic benefits of stockholding are:

- reference market conditions
- oil supply disruption likelihoods
- spare oil production capacity
- emergency oil stock capabilities
- market responsiveness (price elasticities of supply and demand)
- macroeconomic sensitivity to shocks (GDP elasticities).

Details of the BenEStock model are available in Leiby et al. (2016), and Annex 1 provides more details on model components and inputs that are specific to the current study. Annex 2 shows the complete list of assumptions based on extensive discussions with IEA staff and delegates of the SEQ.

In the BenEStock model, a co-ordinated action is triggered if an "oil shortfall" is larger than a predefined drawdown threshold level. The oil shortfall is calculated as the size of the supply loss following a disruption, reduced by certain offsets. Offsets include oil production from spare capacity, short-run demand switching and increased production from elastic supply sources. The latter accounts only for US tight oil production flexibility. The model assumes that if the net disruption (after these offsets) is greater than the specified drawdown threshold level, emergency stocks will be used in a co-ordinated action.

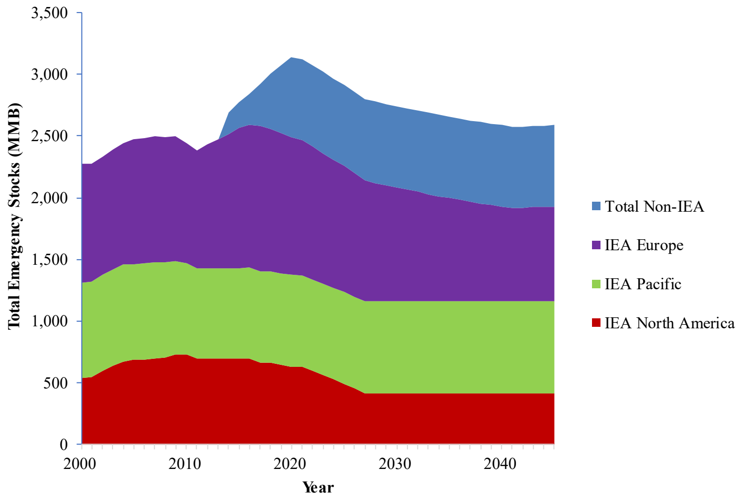
A drawdown threshold of 2 mb/d is used for the central case in this report. Drawdown rates for each stock type (i.e. public and obligated industry) are limited by the specified technical maximum drawdown rate for that year, the specified drawdown rule or strategy, and the rate of exhaustion.

After a drawdown, the emergency stocks can be refilled at exogenously specified refill rates. If the oil shortfall is greater than zero, the world oil price is affected. Under the central case assumptions, if the oil shortfall is zero (i.e. the net disruption is fully offset by emergency stocks), the possibility is considered that market dislocation, speculative behaviour or a risk premium will prevent stocks from completely eliminating the price increase. Oil price increases are translated into economic costs to society, composed of GDP losses, net oil import costs, and social surplus losses. Net revenues from emergency oil stock sales and refill purchases are also calculated.

3.1 Existing IEA stocks and drawdown capabilities

The economic benefits of IEA stocks result from the capability to offset future supply disruptions. This offset capability, in turn, depends on the size and drawdown rate of IEA stocks. Total world emergency stocks are displayed in Figure 7. IEA stocks vary slightly as future impacts and obligations vary, but average 2.14 billion barrels annually over the 30-year planning horizon from 2018-47.

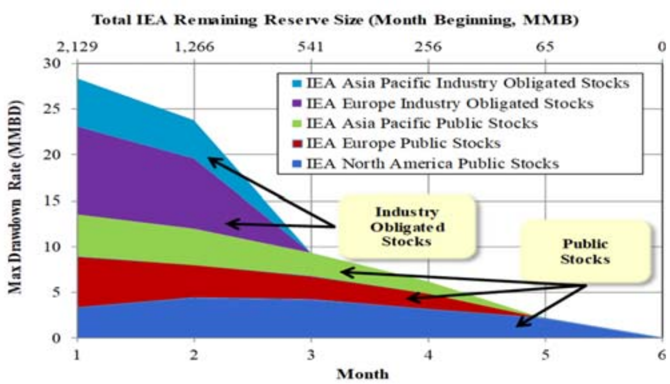
Figure 7 • Total emergency stocks (end of year, mb)



Note: Figure includes: 1) publicly-held or publicly-controlled non-US IEA stocks for end of year 2015; 2) stocks held by industry under compulsory stockholding obligations; and 3) non-IEA emergency stock estimates (see Annex A).

The maximum achievable drawdown for combined IEA stocks is initially quite large: 11 mb/d for public stocks in the first three months, and an additional 13 mb/d if industry-obligated stocks are fully available, for up to two months. After the first two months at this rate, the maximum drawdown rate would drop dramatically as industry-obligated and some regional public stocks reach exhaustion. Figure 8 displays the maximum drawdown rates over a six-month horizon. Additional details on the estimated relationship between draw rate and stock can be found in Annex 1.

Figure 8 • Year 2025 – maximum drawdown rate as a function of remaining effective emergency stock size



Note: The drawdown is constrained by first-month startup delay, maximum system capability and exhaustion; the size is actual size less unrecoverable amount.

This analysis assumes that IEA countries holding emergency oil stocks will engage in collective withdrawal when available spare production capacity is not enough to bring supply disruption below a threshold level. In the base case, the net supply loss (after spare production capacity has been utilised) must be above 2 mb/d to trigger emergency stock releases. Alternative drawdown thresholds are also considered. If the threshold is exceeded, the drawdown strategy is to draw at the rate necessary to fully offset the net shortfall, up to the maximum technically feasible rate, for the first three months. After three months, if the disruption persists, drawdown slows to the maximum sustainable rate for the expected duration of disruption.

The projected total drawdowns are generally larger than the (limited) historical drawdowns over the last three decades, for two reasons. First, the potential disruption events in the Energy Modeling Forum (EMF) 2015 summary include the possibility of some very large and long events. Second, the analysis assumes prompt and co-ordinated drawdowns to fully offset the disruptions that exceed the stated threshold, and for as long as the disruption continues. From the simulation results, the mean total drawdown for a 3-month disruption is 363 mb; for the rarer 12-month disruption it is 1 096 mb and the 18-month disruption is 1 313 mb. There have been large and long events in the past, from 1956 to 1991, but then either there was no stock available to release, or no sale was activated. Since 1992, the actual historical sales have all been limited, in comparison with the abilities of the IEA stocks (about 60 mb total at 2 mb/d over 30 days).

3.2 Economic benefits for sample year 2025 disruptions

While the economic benefits of stocks are calculated from a probability-weighted average of many thousands of possible 30-year futures, with a wide range of disruption outcomes, from no disruption to quite potential supply losses, the economic benefits of an IEA collective release can be illustrated with three example scenarios for the year 2025. The following discussion considers a large and long disruption (9 mb/d, 12 months), a smaller but equally long disruption (3 mb/d, 12 months), and a smaller, short disruption (3 mb/d, 3 months). These cases were chosen to illustrate the range of supply losses that may be addressed with IEA stocks. The 9 mb/d case exceeds the size of any disruption to date, and exceeds the replacement capabilities of existing IEA stocks. The scenario is consistent with a variety of possible major events including, for example, a disruption in the Middle East that results in a 30% loss of Saudi Arabia and Other Persian Gulf supply. The 3 mb/d case is comparable to supply losses experienced under a number of historical episodes. It is smaller than the Iraq-Kuwait war of the early 1990s, which was estimated to have taken 4.3 mb/d off the global oil market.

Drawdown rates for the three sample disruption cases are shown in Figures 9-11.[14] The 9 mb/d disruption case is large and long enough that the IEA emergency reserves would be fully exhausted before the end of the disruption, if drawn at the maximum rate. After three months of fully offsetting the disruption, a lower, more sustainable draw path is assumed. For the 3 mb/d disruptions,[15] IEA stocks are large enough to maintain a near uniform draw rate over the disruption duration.

[14] Note that the maximum drawdown rate is generally below the gross supply disruption because emergency stocks are used to mitigate net, instead of gross, supply disruptions. Net supply disruptions are calculated as gross supply disruptions, net of exogenous demand switching and production from spare capacity. Production from spare capacity is delayed until the second month, but exogenous demand switching immediately offsets a portion of the disruption and is by assumption set at 0.35 mb.

[15] Regional draw contributions are based upon relative petroleum consumption. For IEA Europe and IEA Asia and Pacific, industry-obligated stocks are assumed to be drawn down first. Where available, industry-obligated stocks are assumed to be drawn before public stocks, subject to maximum technical draw capabilities.

Figure 9 • Drawdown rates for a sample year 2025 disruption (9 mb/d, 12 months)

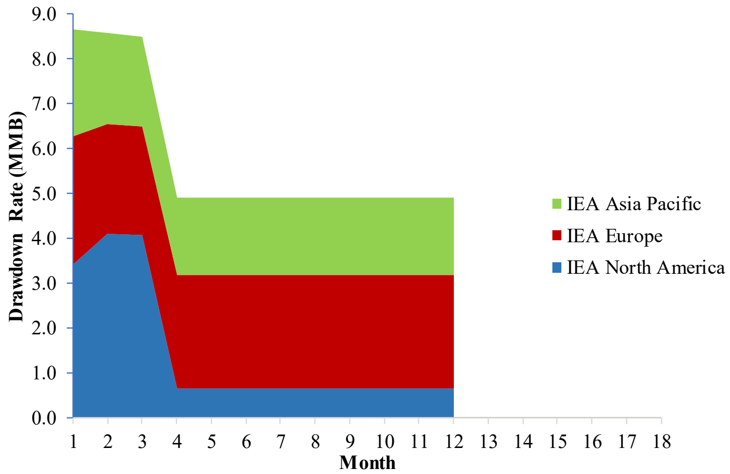


Figure 10 • Drawdown rates for a sample year 2025 disruption (3 mb/d, 12 months)

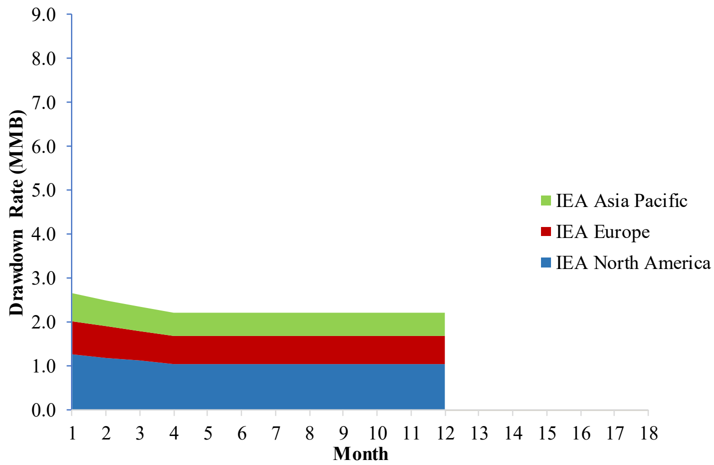
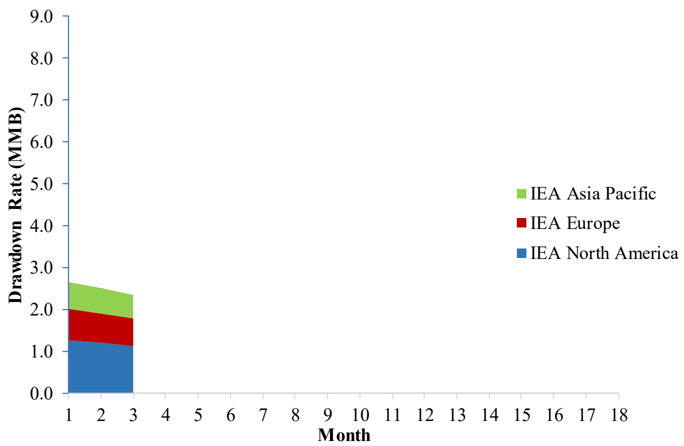


Figure 11 • Drawdown rates for a sample year 2025 disruption (3 mb/d, 3 months)



3.2.1 Price reduction effect

Figure 12 shows the reference, undisrupted, price of oil in 2025 along with the disrupted prices with and without IEA emergency reserve use for a 9 mb/d disruption size.

In the case without an emergency oil stock release from the IEA, oil prices rise from USD 83/bbl to about USD 275/bbl in the first month of the disruption, declining to slightly more than USD 140/bbl at the end of 18 months. In the case where there is an IEA drawdown, prices in the first three months are still about USD 17/bbl above the reference price despite the shortfall being fully offset. This reflects the assumption of a risk premium in oil prices. After three months, as the drawdown rate is reduced to forestall exhaustion, prices rise to over USD 150/bbl, but decline to about USD 110/bbl by the 18th month after the start of the shock.

Figure 12 • Reference and disrupted world oil prices for a sample year 2025 disruption (9 mb/d, 12 months)

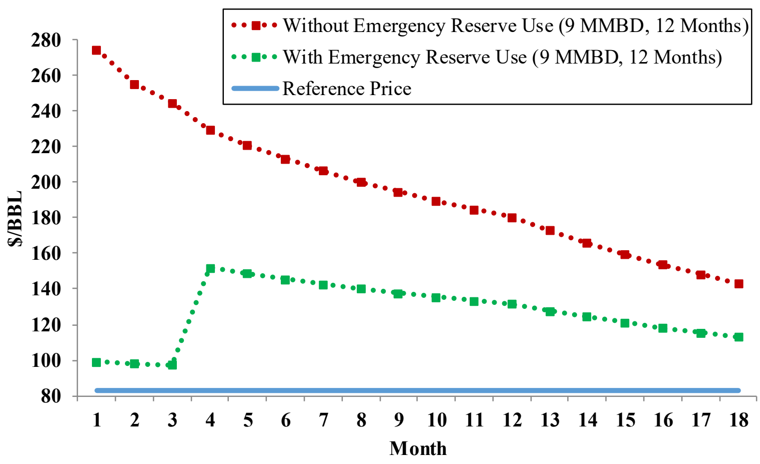


Figure 13 • Reference and disrupted world oil prices for a sample year 2025 disruption (3 mb/d, 12 months and 3 months)

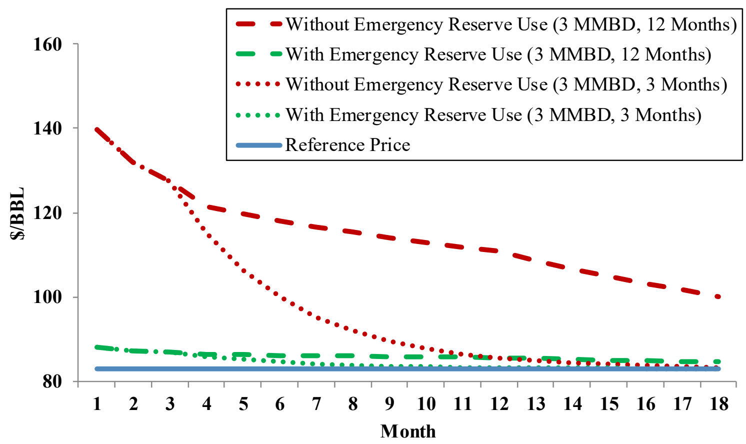


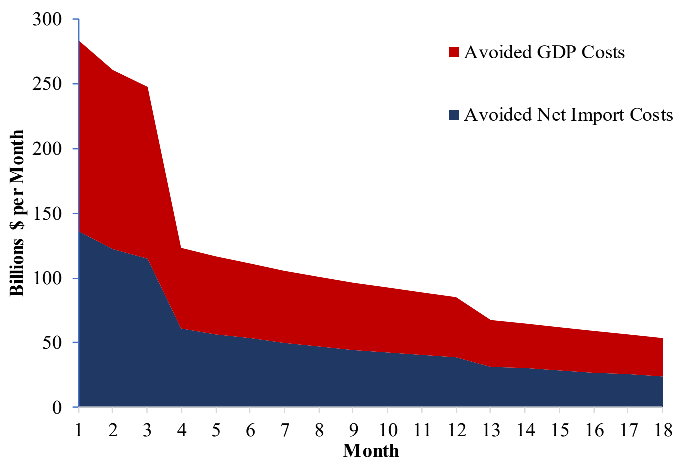
Figure 13 shows the reference undisrupted price for 2025, along with the disrupted price with and without emergency stock use for the long and short 3 mb/d disruption cases. The oil price rises from USD 83/bbl to about USD 150/bbl in the first month in both cases, when emergency stocks are not used. For the longer disruption, the oil price declines gradually to about USD 100/bbl by the 18th month, whereas it declines more rapidly to almost the reference price level by the 12th month under the shorter disruption. In both cases, the use of emergency stocks lowers the oil price to about USD 87/bbl in the first month, remaining close to the reference price throughout the 18-month period following the start of the disruption.

In all the above cases, whether emergency stocks are used or not, prices begin to decline as the disruption continues due to increased responsiveness from the demand side of the market, which becomes more elastic (by assumption) over the course of the disruption. While these are large estimated price increases for the samples of net supply losses, the historical record shows that prices have doubled and more after past significant disruptions (Figure 1). In some historical cases the price effect has also been quite long-lasting. The price increases here reflect the estimated low (and likely declining) short-run flexibility of world oil demand, from a meta-analysis synthesising the results of more than 70 studies published from 2000 to 2015 While there is some evidence that tight-oil production flexibility can make supply more responsive to price shocks, tight-oil supply accounts for only a small fraction of total global supply, much of which is believed to be essentially inelastic in the short run. In addition, even after supply is restored to normal levels at the end of the event, the price does not immediately return to the pre-disruption level but converges over the following months. This treatment captures the persistence of oil price shocks beyond the end of a shock, as determined by the size and duration of the supply disruption.

3.2.2 Benefits from avoided GDP losses and import costs

The economic benefits of emergency reserves are derived primarily from offsetting supply losses and reducing potentially massive price increases. As shown in Figures 14-16, given the stated assumptions of the model, the costs avoided by the IEA and other net importing countries thanks to the release of IEA emergency stocks can range from hundreds of billions of dollars, under smaller and shorter supply disruptions, to over a trillion dollars, under very large and long supply disruptions. The two major types of benefits are reduced GDP losses and reduced net import costs. In these scenarios, and in the simulations to be discussed next, both components are similar in magnitude.[16]

Figure 14 • Monthly benefits of IEA emergency reserve drawdown to the IEA and other net importing countries during a sample year 2025 disruption (9 mb/d, 12 months)



[16] One other small component is the oil sales net revenue. This is the expected value of emergency sales revenues minus subsequent refill costs. It excludes the costs of initial fill.

Figure 15 • Monthly benefits of IEA emergency reserve drawdown to the IEA and other net importing countries during a sample year 2025 disruption (3 mb/d, 12 months)

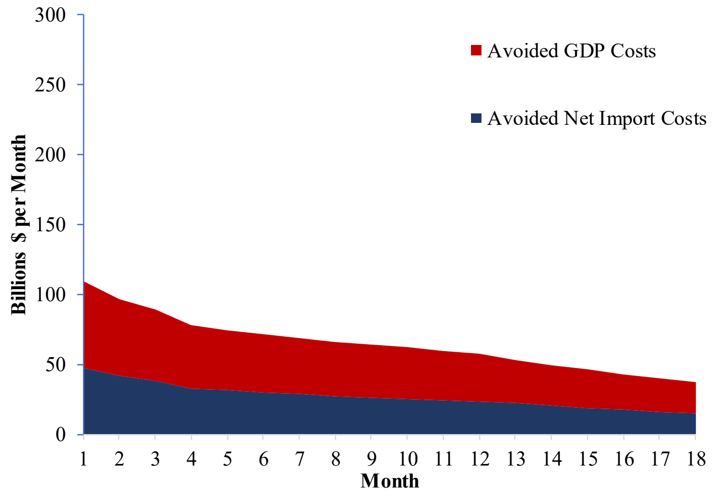
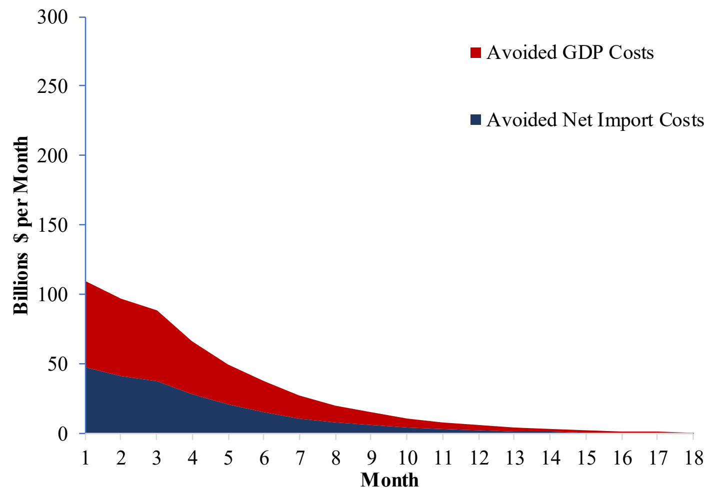


Figure 16 • Monthly benefits of IEA emergency reserve drawdown to the IEA and other net importing countries during a sample year 2025 disruption (3 mb/d, 3 months)



3.3 Expected cumulative economic benefits over 30 years

Emergency stockpiles constitute a long-term investment so that the benefits and costs of these programmes must be evaluated over long time horizons. The BenEStock model simulates the benefits from emergency stocks in response to a wide range of possible disruptions over a 30-year period (2018-47) using randomly generated future time paths for oil supply and price. A base case and several alternative scenarios were explored.

The base case assumes:

- IEA reference price and quantity path from the IEA 2017 *WEO* New Policies Scenario.
- Co-ordinated release of IEA emergency oil stocks.
- Disruption risk attributes based on EMF 2015 assessment.
- A supply loss threshold of 2 mb/d before the IEA takes collective action.

- The drawdown strategy, once the threshold is exceeded, is a prompt co-ordinated draw at the maximum draw rate technically possible aimed at fully offsetting the net shortfall, for the first three months. After three months, drawdown slows to a sustainable rate for the expected length of disruption.
- Industry-obligated stocks are 100% available for use in close co-ordination with public stocks.
- Full offset of net shortfall does not completely restore the market to its pre-disruption state (due to, e.g. risk premium or speculative behaviour).
- Monte Carlo-type simulations with 10 000 replications are used to estimate expected values and confidence intervals of net benefits and other relevant variables. This simulation generates randomised values for disruption sizes and durations (3 months to 18 months), spare capacity availability, and GDP sensitivity and demand flexibility (elasticities) over the 30-year horizon.

A summary of the measure of stockholding benefits is the annual benefits per barrel of emergency IEA stocks held. Table 4 shows the average and 90% interval of benefits of IEA stocks. The average collective total benefit is about USD 61/bbl per year of ownership, under base assumptions. This is a very substantial value, representing the expected average annual outcome over 30 years and over many possible sequences of market outcomes, discounted to 2016 dollars at 3%. Because the oil market is so uncertain, this USD 61/bbl per year represents an average payoff from the insurance provided by stocks, so the actual benefits could be smaller or much larger. The 90% interval for benefits under base case conditions reflects uncertainty about these oil market outcomes, particularly about which disruptions might occur and when over the 30-year planning horizon. It ranges from USD 11.0/bbl to USD 119.5/bbl per year. Table 4 also provides undiscounted estimates of average annual benefits per barrel for comparison.

Table 4 • Average annual stockholding benefits per barrel (USD/bbl per year), based on total IEA stocks, base case (low to high range encompasses 90% of the sample distribution)

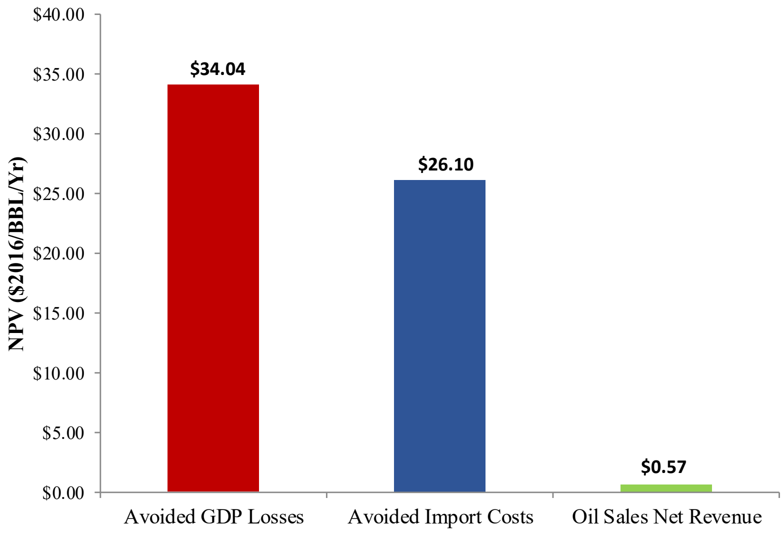
Benefits of current IEA versus no emergency stocks	Low	Average	High
3% discounting (base case)	10.96	61.27	119.47
0% discounting (alternative case)	16.99	99.38	192.77

Figure 17 displays the discounted average annual per-barrel benefit for three components of benefits.[17] It shows that avoided GDP losses are the largest component, reflecting the importance of curbing oil supply shocks to avoid damaging impacts throughout the entire economy. The net import cost savings component is similar in magnitude to the avoided GDP losses, and reflects the level of dependence by IEA and other net importing countries on oil imports, as well as the price reduction benefits of using emergency stocks to mitigate oil supply disruptions.[18]

[17] This benefit value includes small net revenue from stock sales revenue less repurchase costs from refilling, but does not account for any other costs. Specifically, it excludes initial oil purchase costs, facilities costs, and facilities operation and maintenance costs, but includes small drawdown and fill transactions costs.

[18] Canada is aggregated into a group with other IEA members. The changes to Canadian oil import revenues from disruptions and stock use are thus included, and act to offset the changes in import costs of net importing IEA countries.

Figure 17 • Total benefits of IEA stocks over 30 years, by component (base case), including global benefits to all oil-importing countries



Note: NPV = net present value.

Table 5 presents the total calculated benefits for the base case in three ways, and for discount rates of 3%.[19] It shows that the base annual discounted benefit of USD 61/bbl corresponds to a total benefit of about USD 4 trillion over 30 years.

Table 5 • Total stockholding benefits to the oil importing countries: Alternative measures

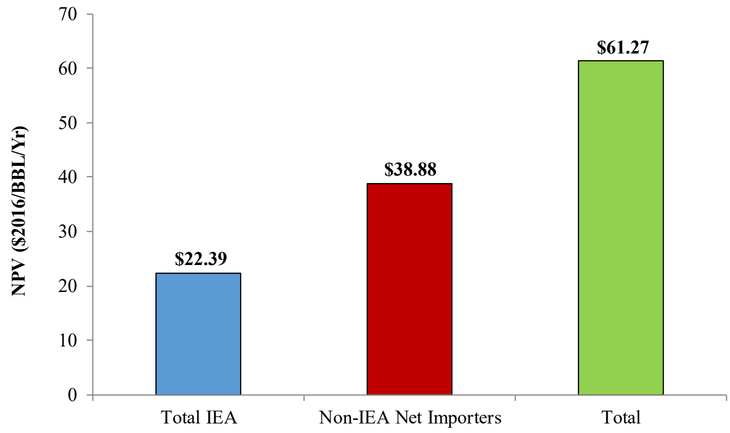
Discounting	Base discount rate (3%)		Undiscounted (0%)	
Units	Total benefits over 30 yrs., billion USD 2010	Annual benefit, USD/bbl per year	Total benefits over 30 yrs., billion USD 2010	Annual benefit, USD/bbl per year
Current world vs. no stocks	3 925	61.27	6 367	99.38

The total benefits derived from IEA emergency stocks comprise benefits for IEA countries and benefits for non-IEA net oil importing countries (Figure 18). In this analysis, the benefits enjoyed by non-IEA countries are higher than the benefits to the IEA.[20] The principal reason for this is that non-IEA oil consumption and GDP are projected to grow significantly over the 30-year horizon of the simulation, eventually exceeding collective consumption and GDP of IEA member countries. The high share in oil consumption and GDP is reflected in a high share of the benefits derived from stocks during a supply disruption.

[19] As mentioned, discounting adjusts future benefits to account for the time value of money, i.e. the greater value of USD 1 now compared with one year from now. Unless otherwise specified, annualised or total (NPV) benefits are computed by adjusting the benefits over time with a 3% annual discount rate. Because of the long planning horizon, all of these benefit figures are much larger when considered in undiscounted terms, as Table 5 indicates.

[20] As noted in Annex 2 (full list of assumptions), non-IEA stocks are not assumed to be available in the base case. However, sensitivity cases with 50% and 100% availability of non-IEA stocks used in co-ordination with IEA stocks are discussed below. Co-ordination of emergency stock uses in all cases is based on consumption shares.

Figure 18 • Discounted average annual benefit per barrel per year of IEA stocks, by benefits region (base case), including global benefits to all oil-importing countries.

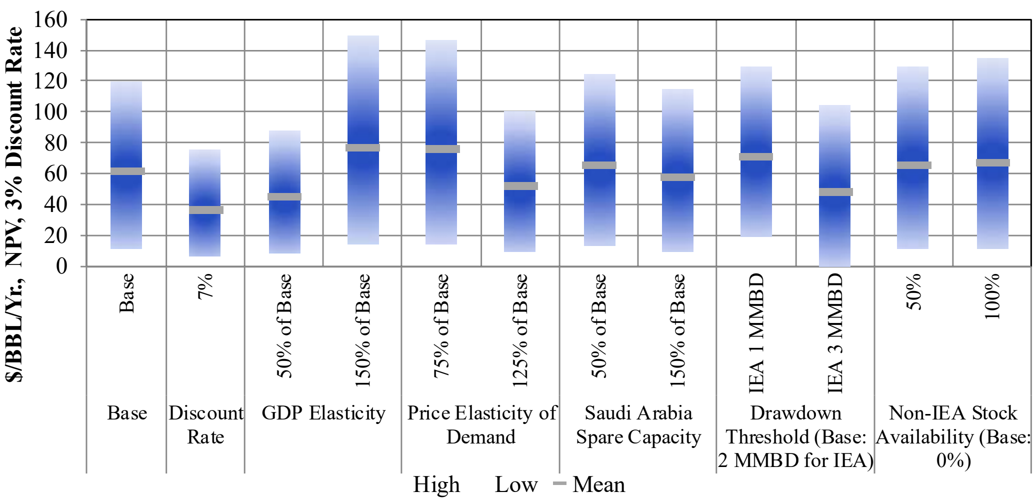


3.4 Sensitivity of economic benefits to major influencing factors

Analyses were performed to examine the sensitivity of the net benefits of IEA stocks to key driving factors. The factors examined are discount rates, GDP sensitivity to oil price shocks, petroleum demand and supply flexibility in the short run, spare oil production capacity, drawdown threshold, and availability of non-IEA stocks.

Figure 19 shows the mean and 90% confidence interval of net benefit estimates for the base and sensitivity cases in USD/bbl per year.[21] Table 6 presents the mean and 90% confidence interval of total benefits over 30 years for these sensitivity cases. Annex 3 shows a table of the estimates in Figure 19 in USD/bbl per year. Table 7 shows the mean estimates by benefits region in USD/bbl per year.

Figure 19 • Benefits of emergency stockpiling for variety of sensitivity cases – USD/bbl per year



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[21] All values are calculated using the IEA emergency stock level in the denominator to provide a common basis for the estimates.

Table 6 • Total benefits over 30 years (billion USD 2016) – low to high range encompasses 90% of the sample distribution

Case	Low (5%)	Average	High (95%)
Base case	702	3 925	7 654
Discount rate (7%)	389	2 315	4 812
Lower GDP response (~50% smaller elasticity than base)	511	2 897	5 650
Higher GDP response (~50% of larger elasticity than base)	888	4 932	9 573
Less elastic net demand (25% smaller elasticity than base)	895	4 843	9 383
More elastic net demand (25% larger elasticity than base)	578	3 303	6 455
Saudi Arabia slack capacity less available (50% vs. 100%)	831	4 197	7 972
Saudi Arabia slack capacity more available (150% vs. 100%)	602	3 691	7 323
Drawdown threshold, mb/d (1 for all IEA vs. 2 for all IEA)	1 217	4 547	8 281
Drawdown threshold, mb/d (3 for all IEA vs. 2 for all IEA)	0	3 094	6 682
Non-IEA stock availability (50% vs. 0% base)	702	4 155	8 263
Non-IEA stock availability (100% vs. 0% base)	702	4 306	8 650

Table 7 • Total benefits over 30 years by benefits region (USD/bbl per year)

Case	IEA	Non-IEA net importers	Total
Base case	22.39	38.88	61.27
Discount rate (7%)	13.99	22.15	36.14
Lower GDP response (~50% smaller elasticity than base)	14.50	30.72	45.22
Higher GDP response (~50% of larger elasticity than base)	30.12	46.86	76.98
Less elastic net demand (25% smaller elasticity than base)	27.33	48.27	75.60
More elastic net demand (25% larger elasticity than base)	18.98	32.57	51.56
Saudi Arabia slack capacity less available (50% vs. 100%)	24.00	41.52	65.51
Saudi Arabia slack capacity more available (150% vs. 100%)	21.00	36.62	57.62
Drawdown threshold, mb/d (1 for all IEA vs. 2 for all IEA)	26.10	44.87	70.98
Drawdown threshold, mb/d (3 for all IEA vs. 2 for all IEA)	17.43	30.86	48.29
Non-IEA stock availability (50% vs. 0% base)	23.45	41.41	64.86
Non-IEA stock availability (100% vs. 0% base)	24.13	43.08	67.22

Discount rate: The discount rate is used to convert estimates of future benefits into NPV to account for differences in the value of money over time, representing the opportunity cost of delaying expenditures today or the rate of time preference. The appropriate value of the discount rate depends on many factors, including source of funds, affected stakeholders and level of risk.

For public assets, such as emergency stocks, the discount rate of benefits is often assumed to be the risk-free interest rate on government funds. However, alternative discount rates for public assets may apply depending on the above factors. A base discount rate of 3% is used in this study for calculating the NPV of benefits.[22] Tables 5, 6 and 7 show that increasing the discount rate from 3% to 7% reduces the NPV of IEA stock benefits by more than one-third.

Sensitivity of the economy to oil price: Sensitivity of the economy to oil price shocks depends on many factors including energy intensity of GDP, share of oil in the energy mix, availability of alternative fuels for specific use (as in transport), oil import share, per capita GDP and technological change, among others. On the one hand, rapid growth in per capita GDP in emerging markets has increased their consumption and dependence on imported oil, potentially making them more vulnerable to global oil supply disruptions. In contrast, many countries are pursuing alternative transportation fuels and promoting increases in vehicle fuel efficiency that would reduce the sensitivity of their economies to oil market changes.[23] A 50% reduction in the sensitivity of oil-importing economies to oil prices leads to a decrease in net benefits from about USD 61/bbl per year to about USD 45/bbl per year. When the average sensitivity of oil-importing economies increases by 50%, net benefits increase by 25%, to almost USD 77/bbl per year. Thus, an increase in the sensitivity of the economy to oil prices makes stockholding more valuable.

Short-run flexibility of demand and supply: When a supply loss occurs, the ultimate price increase will depend on the extent to which demand as well as alternative supplies can adjust in response to rising price signals in the short run. This short-run flexibility is summarised by the "elasticity of net petroleum demand." Smaller elasticity, or lower flexibility, of demand requires higher price levels to clear the market, given the same market shock. If the future elasticity of petroleum demand is 25% less than assumed in the base level, the mean estimate of net benefits increases from USD 61/bbl per year to about USD 76/bbl per year, whereas it declines to about USD 52/bbl per year if the elasticity is greater by the same percentage. Elasticities are generally quite small in the short run, and expected to be lower in some sectors (e.g. transportation), and regions (e.g. newly industrialised countries). Emergency stocks can become substantially more valuable as the petroleum market becomes less flexible, and concentrated in these more inelastic sectors and regions. Conversely, the need for stocks can be somewhat reduced if other measures and technologies are found to improve short-run demand flexibility.

Saudi Arabia spare capacity: Availability of spare capacity from undisrupted producers reduces the call on IEA stocks during oil supply disruptions. Data show that the OPEC spare capacity for oil production has fluctuated from a high of 6.3 mb/d to less than 2 mb/d over the last two decades. Saudi Arabia is the major swing producer in the global oil market and holds most of the current OPEC spare production capacity. The period of sustained high oil prices from 2003 to 2008 was characterised by very low OPEC spare production capacity. After a jump in spare capacity to about 5 mb/d following the global financial crisis in 2009, the spare capacity level dwindled rapidly and stood at about 2 mb/d at the end of 2017. More important than the nominal level of spare capacity is the uncertainty that this capacity would be made available during a global supply disruption. Given this, OPEC spare capacity availability is specified using a random distribution based on the EMF 2015 assessment of global oil disruption risks.

Sensitivity analyses are used in this study to examine the effect of lower and higher levels of Saudi Arabia's spare capacity on the benefits of IEA stocks during an oil supply disruption. The base case assumes that the maximum possible Saudi spare capacity would be about 2 mb/d, with a random availability distribution and expected value of 1.1 mb/d. For the sensitivity analyses,

[22] Note that this is the real discount rate (excludes inflation) since it is applied to real USD 2016 values in this study.

[23] The sensitivity of the economy to the oil price is captured by the GDP elasticity parameter in this study. Potential shifts in this parameter for all regions are considered to evaluate the effects of changes in future sensitivity of oil-importing economies to oil prices on the benefits of the public IEA stocks.

the two alternative cases assume a reduction of +/-50% change in the Saudi spare capacity. Of course, the actual use of spare capacity in the event of a disruption will be situation-dependent. In particular, Saudi spare capacity is not available under those scenarios where the disruption is from an event happening in Saudi Arabia. Figure 19 shows that a 50% decrease in spare capacity increases net benefits of IEA stocks to USD 66/bbl per year, whereas increasing the availability to 100% reduces the benefits to about USD 58/bbl per year. The small effects of these cases on benefits reflect the fact that these are shifts in spare production capacity, rather than availability, since availability is determined by a random distribution during the simulations.

Drawdown threshold: IEA oil stocks are generally reserved for emergencies where unmitigated oil supply disruptions would cause significant economic damages. Thus, in deciding when to draw down stocks, the IEA would seek to exclude supply disruptions that are unlikely to produce significant changes in oil prices or that can be effectively resolved by market resilience. The supply disruption threshold for a drawdown decision depends on market conditions, and it is difficult to determine in advance. This study captured this aspect of the IEA response to a supply disruption with a 2 mb/d drawdown threshold for global oil supply net shortfalls under the base case.[24] Two sensitivity analysis cases are examined: drawdown thresholds of 1 mb/d and 3 mb/d. A lower drawdown threshold of 1 mb/d implies more frequent use of the IEA stockholdings. Figure 19 shows that the estimated mean net benefit increases to about USD 71/bbl per year under this case. A higher drawdown threshold of 3 mb/d lowers the mean net benefit estimates to about USD 48/bbl per year. The lower bound estimate in this case is zero, because in some 30-year scenarios the stocks may not be called upon at all given the high threshold.

Non-IEA stock availability: Like IEA public and obligated industry stocks, non-IEA emergency stocks have the potential to reduce net shortfalls during a supply disruption. Non-IEA stocks are increasing in importance as large emerging oil-importing nations act to ensure security of supply. Since they are not part of the IEA collective action process yet, the base case assumes a 0% availability of non-IEA stocks. However, given the potential impact on their economies, non-IEA countries might also withdraw their own emergency stocks during an IEA action. The sensitivity cases examine the availability of non-IEA emergency stocks (50% and 100%) against the base assumption of 0%. Figure 19 shows that the mean net benefits of the IEA stocks increase slightly to about USD 65/bbl per year for the 50% case and to about USD 67/bbl per year for the 100% case.[25] Thus, greater availability of non-IEA stocks contributes positive, but small, incremental economic benefits per barrel of IEA stock.

3.5 Additional benefits of emergency oil stocks

The market impacts and tangible economic benefits of holding emergency oil stocks to address global supply shocks are substantial. Yet the value of emergency oil stocks goes well beyond collective protection against the economic costs of a world oil supply crisis. There are other benefits that were not included in the preceding assessment. Four such additional benefits are: protection against localised oil supply disruptions that may affect domestic markets without triggering an IEA response, protection against shocks in petroleum product markets, diplomatic

[24] Recall that the "oil shortfall is calculated as the size of the supply loss following a disruption, net of offsets and emergency stock draw."

[25] Note that these per-barrel estimates use the same denominator (i.e. the IEA stock level) as all other cases for comparability. However, if the denominator were to include IEA and non-IEA stocks, these values would be smaller, and may be lower than the base estimate. This latter result is due to the decreasing value of an additional barrel of emergency stock given that IEA stocks are already of considerable size, and not often fully drawdown.

benefits and national security benefits. Some of these benefits are difficult to quantify, either because they are highly case-specific, or because they are essentially qualitative and non-economic in nature.

3.5.1 Benefits for domestic disruptions

For a supply disruption to trigger a co-ordinated IEA response, it must be large enough to substantially impact world markets. Local disruptions that do not reach the scale of a global shock can still cause costly problems in countries' domestic petroleum markets and economies, without significantly disturbing the global petroleum market. Events in this category include flooding or low water levels in rivers, hurricanes, strikes, earthquakes, pipeline freezes or failures, and port and other infrastructure problems.[26]

Natural disasters can create localised problems where domestic emergency stocks would help. The ten largest earthquakes and storms (ranked in terms of economic damages) since 1980 have all taken place in countries that are net oil importers.[27] With the exception of hurricanes Katrina and Rita in 2005, none of these events triggered an international emergency stock response.[28] More recently, in 2017, Hurricane Harvey made two landfalls on the US Gulf Coast region, leading to extensive refinery, oil production and port shutdowns. Damages to production platforms were minimal and recovered quickly, with limited impacts on global oil supply. However, up to 20% of US refinery capacity was disrupted due to both refinery damages and dislocations in petroleum supply.

In such cases of domestic natural disaster, countries often unilaterally release emergency stocks. Prominent examples of this include:

- Japan lowered industry stockholding obligations by about 8 million barrels of oil products in response to the 2011 earthquake that shut down 31% of domestic capacity (IEA, 2011).
- China released emergency oil product stocks in the aftermath of Sichuan's 2008 earthquake (Yang, 2008).
- The United States has "lent" oil from the SPR to commercial buyers to address local supply chain problems on nine different occasions since 1991. The size of these exchanges varies from 98 000 bbl to more than 30 mb.

For most oil-consuming nations, the petroleum supply chain is both extremely complex and vulnerable. Major global disruptions lead to widespread costs for net importers, who can expect to benefit from global IEA releases. Many local disruptions, however, involve breakdowns in the supply chain and can be addressed only through domestic stocks.

3.5.2 Benefits from protection against product shocks

While the quantitative benefits analysis above focuses on the value of stocks in possible global crude supply disruptions, holding emergency stocks also offers potential benefits for protection against shortages and/or price spikes of petroleum products that arise independently from disruptions. Some of these are domestic events, as discussed in the previous section. However,

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[26] Stocks were used in Switzerland when the river Rhine was too low to carry barges from Rotterdam. In France, the emergency stocks have been used several times during strikes of tank truckers/road haulers.

[27] EM-DAT, The International Disaster Database (www.emdat.be/).

[28] Although a net oil importer, the United States is also a large producer. These hurricanes hit the centre of the US oil industry, destroying oil platforms and closing down refineries for several months. That's why they stand apart from other natural disasters in being the only ones that triggered a co-ordinated IEA stock response.

other product interruptions can affect regional or global product supply and prices. Events that directly impact petroleum products include unplanned major refinery outages (due to weather events, accidents, etc.) or disruption to critical trade links or distribution infrastructure. Examples of recent product supply disruptions indicate a range of sizes, causes and extent of geographical impacts.

Aside from the upstream damage to oilfields, hurricanes Katrina and Rita in 2005 also produced a product shock that was a contributing factor in the IEA collective action decision. The March 2011 tsunami in Japan, like the Katrina/Rita hurricanes in the United States, destroyed refinery and port facilities and swept away petroleum tanks and gas stations. This led to gasoline rationing, a tightening of jet fuel supplies on the island and a reduction in industry stockholding obligations. A refinery fire in September 2011 that affected Singapore's largest refinery (about one-third of its total refining capacity) led to increases in domestic prices. Although in this instance, supplies to the export market were met with inventories and output from other refineries, the disruption had an international dimension as benchmark fuel prices across Asia are based on Singapore trade (Reuters, 2011).

The changing global patterns of refinery activity, with growing reliance on very large refineries outside IEA membership, and international product trade could pose new risks for product supply. According to BP's *Statistical Review of World Energy 2015*, the level of international product trade in 2015 was 21.5 mb/d, about 55% of the amount physically traded as crude oil (39.7 mb/d). Product trade grew much faster than crude oil trade during the last decade (80% increase for products versus 5% increase for crude). This trend reflects a growing geographical mismatch between the supply and demand of particular products.[29] Most new refining capacity is coming online in ever larger plants in the emerging economies of Asia, the Middle East and South America. In addition, between 2012 and 2015 the tight oil boom lifted refinery operation margins in the United States due to a domestic glut of high-quality light sweet oil. This led to a large increase in US product exports and reductions in net crude oil imports. Following the collapse in oil prices since 2015, ageing, low-complexity refineries in Europe, the US Northeast and Australia have faced a difficult business environment. However, overall US product exports remain elevated and crude oil exports have increased since the removal of a 40-year ban. The expanding global trade in petroleum products may lead to increased regional vulnerabilities to product supply disruptions.

Product shocks, in general, have more localised effects than crude oil shocks both geographically and within the economic structure of a given region. While they might have large effects on particular industries (e.g. jet fuel for aviation industry) or customer types (e.g. heating oil for residential customers with no heating appliance substitutes), their macroeconomic impact should be expected to be somewhat smaller as any petroleum product will be an input to a smaller number of productive processes than crude oil (and given that a crude oil shock would also entail a petroleum product shock while the opposite does not automatically hold). While most economic studies of macro effects have limited their attention to crude shocks, there is some evidence indicating the economic impacts of major petroleum product disruptions, such as from the 2005 hurricane events of Katrina and Rita (Cashell and Labonte, 2005; Hamilton and Brown, 2006).

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[29] For instance, the United States has been exporting increasing amounts of refined petroleum products accompanied by reductions in net oil imports. Moreover, road transportation fuel demand projections in the traditionally largest demand centres (mostly Europe and North America) are flat or slightly decreasing due to a combination of vehicle ownership saturation, lower economic growth and increased vehicle efficiency.

Emergency stocks can be stored as crude or product. The usefulness of crude oil stockpiles to respond quickly to product shocks depends on how close, accessible and flexible excess refinery capacity is. Regionalised product stocks have the merit of promptness and specificity to a product shock. Logistical considerations become paramount when trying to alleviate petroleum product shocks, since product shocks immediately and directly affect end-use consumers who do not have the option to store these products themselves. Product stocks can cover logistical lags between the time a shock takes place and the time in which emergency crude oil stocks could become available as products in demand centres. For these reasons the European Union obliges its member states to have at least one-third of their oil emergency reserves as product reserves.

3.5.3 Diplomacy benefits

Concern about oil supply reliability and costs often causes importing states to incur severe costs in the area of foreign relations. In both cases, if importers make domestic or foreign policy decisions with access to oil in mind and exporters use their hydrocarbons as leverage, importers can be easily placed at a disadvantage. Many of the diplomatic problems related to oil imports will remain challenging as long as oil is globally traded. Emergency oil stockpiles, however, can ameliorate some of them by diminishing the impact of oil supply disruption risk.

The diplomatic costs of oil dependency and insecurity have been studied at length in the American context. Some of the insights extend to other importing nations. In 2006, the Council on Foreign Relations (CFR) issued a report that specifically addressed five foreign policy costs of oil dependence (Deutch and Schlesinger, 2006). Emergency oil stocks mitigate at least three of these costs, to varying degrees.[30]

The CFR report points out that individual national responses to oil supply disruption are often hurried and ineffectual. Ongoing foreign policy initiatives can be delayed or altered to address immediate supply concerns. Oil stockpiles can be used to address short-term market concerns, allowing foreign policy decision makers to respond to an international crisis involving an oil supply interruption in a more deliberate manner that is consistent with their longer-term interests.

The CFR task force also notes, as a second cost, that state responses to energy insecurity can undermine the efficient functioning of the global energy market. From non-OECD nations' pursuit of long-term bilateral oil supply arrangements to US oil export regulations, countries subvert the market to facilitate long-term supply security.[31] While emergency oil stocks represent a short-term instrument for dealing with market disruptions, and do not address issues associated with long-term oil dependence, by reducing a country's vulnerability to supply disruptions they can reduce the need for non-market mechanisms for securing supply.

Third, the CFR task force discusses emerging alliances that are forming between importing nations and producers that displace other foreign policy objectives or decrease the influence of other major countries on the global stage. To the extent that new importers can bolster their energy security through developing emergency stocks, the value of maintaining alliances with producer states will potentially diminish. More importantly, increased multilateral co-operation

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[30] The CFR task force also highlighted diplomacy costs associated with the greater exercise of power by some petroleum exporters, based on petroleum revenues, and the problems caused by poor governance within exporting countries. These are not expected to be significantly influenced by oil stocks.

[31] The 40-year ban on US crude oil exports was removed by an act of Congress in 2015 (www.congress.gov/bill/114th-congress/house-bill/702).

in stockpiling and release management could reduce the need for developing preferential bilateral relationships with supplier states.

The adverse impact of oil import dependency is not unique to IEA countries. Since becoming a net oil importer, China has undertaken numerous foreign policy initiatives aimed at enhancing its energy security (Downs, 2000; Lai, 2007; Taylor, 2006; Erickson and Collins, 2010). Many of these policies have proven very costly. The same holds true for India (Brookings, 2007). Both countries are currently engaged in building emergency oil stocks, which will strengthen supply reliability and provide diplomatic benefits at the margin. As countries feel that their oil supply is more secure over time, their freedom of action in some areas of foreign policy will increase. Although this benefit is difficult to quantify, it is doubtless a benefit of holding emergency oil reserves.

Smaller importers also face vulnerability due to oil imports. In many cases, exporting states deliberately pursue policies to increase their leverage over importers. Venezuela's Petrocaribe initiative has been characterised as an example of an oil producer that deliberately used its oil exports to gain leverage over importers (Clem and Maingot, 2011).

In yet other cases, diplomatic disputes between two conflicting parties can render the oil supply of a third-party state insecure. An example of this phenomenon occurred in 1965 when a British oil embargo levied against Southern Rhodesia (now Zimbabwe) led to severe petroleum shortages in Zambia, whose imports mostly arrived through the target country (Dietrich, 2011). Zambia was forced to subvert its foreign policy preferences and seek help from the Portuguese government that still held Mozambique as a colony. Although this took place decades ago, the logic is instructive for small states that depend on third-party states for oil transit. Even a small buffer of emergency stocks against the potential manipulation of activist exporters or the fallout of other external disputes can be beneficial to the diplomatic position of importers in situations like those outlined above.

3.5.4 National security benefits

For many oil-importing nations, there is strong agreement that oil security and national security are closely connected (e.g. CAN/MAB, 2011: xi). In this section, the potential benefits of petroleum stocks for defence and national security objectives are considered.

The Carter doctrine is generally considered as marking the beginning of a trend towards militarisation of energy security over the last three decades. The United States has been the most heavily involved country in military operations related to energy security, and therefore has the largest associated defence costs. However, other North Atlantic Treaty Organization (NATO) countries have been involved in military conflicts in the Middle East, too. NATO and the European Union's Common Security and Defence Policy allow military intervention with the goal of energy security and have focused on missions related to protection of critical energy infrastructure assets. Meanwhile, the development of assets and capabilities for keeping watch over vital sea lanes of communication in the South China Sea is one of the objectives China pursues with its increased military expenditure over the last decade (Pennington, 2011). Following the US tight oil boom and the oil price collapse of 2015, OPEC has co-ordinated actions to restrict oil production with Russia, even as Russia's military involvement in the Middle East grew.

Past studies of oil security costs generally concur that the military and national security implications of oil use are complex and difficult to disentangle and quantify (e.g. Toman, 1993; Leiby, 1997; Parry and Darmstadter, 2003; RAND, 2009). Early studies (Ravenal, 1991; Kaufmann and Steinbrunner, 1991; US GAO, 1992; Hall, 1992; Toman, 1993; Koplow and Dernbach, 2001; Copulos, 2003; Parry and Darmstadter, 2003) produced a wide range of military cost estimates, associated with the protection of oil production and transit. These were typically based on a period of substantially lower military budgets and oil prices. Those costs ranged from USD 4.7 billion to USD 64 billion per year.

The estimated ranges from more recent literature, summarised in Table 8, are generally higher than in previous studies, and there seems to be more confidence that the military cost that could be avoided with a partial or complete reduction in concern about imports supply risk is substantial.

Table 8 • Estimates of the military cost of oil security missions (billion USD 2010/year)

Study	Low	High
Copulos (2007)	154	154
Delucchi and Murphy (2008)	21	68
RAND/Crane et al. (2009)	76	92
Stern (2010)	314	523

Military costs include programmes serving to protect shipping routes through maritime choke points (e.g. Strait of Hormuz and Strait of Malacca), to limit the ability of other states to interfere with oil-supplying regions, and to reduce the likelihood of disruptions. The continued naval presence in these areas, mostly by the US Navy but also by other NATO countries, to ensure free transit of oil (and other commodities) is expensive. Co-ordinated releases of emergency oil stocks would dampen the effects of production losses due to choke-point disruptions.

Petroleum fuels play a critical role for national defence operations. So vital are oil supplies for US military operations that the SPR holds some oil for the Department of Defense. The sharp increase in petroleum intensiveness of military operations and concern about the human and financial costs of assuring reliable fuel supply during wartime (Deloitte, 2010; US DoD, 2011) has led to many energy-security initiatives by the US military (US DoD Energy Security Task Force, 2006). The world oil price increases at the onset of military conflicts motivated by energy security concerns and/or taking place in countries that are large oil exporters. Moreover, during wartime, the probability of temporary supply interruptions soars. Therefore, significant savings can ensue if the military can draw from emergency stocks rather than having to buy all of its petroleum fuels in the market.

Some analysts point at energy security as the most likely concern that could make advanced societies go to war (Moran, 2010; Stern, 2010). Stockpiling, by reducing exposure to oil shocks, can also diminish the defence and national security costs of oil use. Co-ordinated releases of emergency oil stocks would dampen the effects of production losses due to choke-point disruptions or production losses due to wars or political reasons. Emergency oil stocks raise the threshold (in size and/or duration) of disruptions that would require military or foreign policy intervention. Moreover, stocks assure supply, attenuate logistical risks and reduce energy costs incurred by national defence forces when their action is required.

This qualitative discussion of additional benefits has summarised a wide range of potential stock benefits, possibly large in magnitude, that are excluded from the prior quantification of avoided economic loss during global supply disruptions.

Emergency oil stocks reduce vulnerability to other kinds of risks. First, they help in coping with domestic shocks (from natural disasters to infrastructure outages) that are large and/or persistent enough to damage the national economy but not large enough to trigger a co-ordinated IEA response. Second, they lead to improved diplomatic positions for importing countries in relation to oil-exporting, sometimes politically unstable, nations. Third, they can reduce the need for military preparations or intervention for energy security reasons. They also help guarantee the ability of the national defence sector, which is highly oil intensive, to conduct any other operations related to national security. The relative importance of these different categories will vary across countries, and it is at the country or regional level that these other benefits would best be evaluated.

3.6. Conclusions of the benefits estimates

A future of continued, and potentially growing, oil market risk: The long history of oil supply disruptions, with resulting price shocks, creates concern about future risk. Most of the large historical supply losses occurred in the OPEC region. Although US oil production has increased since 2012, expectations are that global reliance on oil supply from potentially unstable sources, including OPEC, will remain significant. Both the IEA and OPEC expect OPEC petroleum production to remain flat until 2025 before growing to account for almost 50% of world supply. At the same time, IEA and the US EIA both project a future of low spare oil production capacity. Under these conditions the prospective need for, and value of, buffer stocks is notably greater. In that context, this study evaluated the future benefits of IEA emergency oil stocks.

Economic benefits estimated by computer simulation of possible oil disruptions: Given uncertainty about the wide variety of possible future oil market outcomes, estimates of economic benefits are produced by simulating thousands of future global oil disruption sequences and calculating changes in price, GDP and net import costs with and without the use of IEA emergency stocks. This produces measures of global economic benefit to all oil-importing countries, including mean (expected) values and high-low intervals.

Large capability of IEA stocks, but risk far from eliminated: The current emergency stocks held in combination by IEA countries, when used in a co-ordinated manner, are capable of significantly reducing the expected costs of many potential future shocks. During large or long disruptions, which cannot be fully offset by emergency stocks, drawdown still provides significant partial price protection and reduces costs to oil-importing regions by hundreds of billions of dollars globally. As illustrated in the single-year disruption sample scenarios, without emergency oil stocks, the price of oil could double or triple in a very large disruption. With IEA emergency stocks, the price increases are much more manageable. However, substantial unaddressed disruption risk and cost remains in those cases. For instance, for a large (9 mb/d) event lasting 12 months, even the complete use of all IEA stocks avoids only about half of the initial disruption costs.

Base case benefits on the order of USD 60/bbl per year: Current IEA stocks provide a collective total benefit of USD 61.27/bbl per year over the 30-year planning horizon.[32] This is the mean or average benefit from the "insurance" provided by stocks, although like any insurance policy, the actual benefits would depend on the particular oil market future ultimately realised. The 90% interval for benefits under base case conditions reflects uncertainty about oil market outcomes, and ranges from USD 10.96/bbl to USD 119.47/bbl per year.

Two roughly equal benefit components: Emergency stocks, by reducing the price shock after a supply loss, help reduce GDP losses and oil import costs. For a given country, the relative magnitudes of these two components depend on that country's level of imports and macroeconomic sensitivity to shocks. The total benefits to world oil-importing nations from the

[32] This is the base case mean value.

two cost components are roughly comparable in size. For the base case, the two major benefits components amount to USD 34.61 /bbl for avoided GDP losses and USD 26.10/bbl per year for Avoided import costs (Figure 17). Contributions from net oil revenue sales are one order of magnitude smaller (USD 0.57/ bbl).

Sensitivity cases show variation in benefits for each case: As part of this study, the expected net benefits (and confidence intervals) for a number of sensitivities were estimated. The range of sensitivities encompasses a wide variety of potential future oil market outcomes, both optimistic and pessimistic. Expected benefits of emergency stocks appear robust, generating at least USD 2.3 trillion in NPV or USD 36/bbl per year and as high as USD 5 trillion or USD 77/bbl per year for the most pessimistic oil market cases. The sensitivity analysis also highlighted factors that could change both the likelihood and economic costs of oil price shocks over time, and the need for emergency stocks. Adverse factors include the expectation of lower spare oil production capacity relative to the levels of at-risk supply, and global patterns of development and increased fuel use that may decrease overall demand flexibility and increase global sensitivity to oil prices shocks.

The 90% confidence intervals demonstrate a wide range of possible outcomes: The confidence intervals presented show a variety of outcomes within a standard 90% probability of occurring. In most cases, the outcomes suggest benefits of at least USD 511 billion or USD 8/bbl per year, except in the case of a 3 mb/d drawdown threshold. In that case, the drawdown threshold can, under certain scenarios, eliminate the need for emergency stocks throughout the 30-year period. However, the drawdown threshold is a policy choice, and such an outcome is avoidable. Conversely, benefits can be quite high, up to USD 9.6 trillion or USD 149/barrel per year, for the higher end of the confidence interval range, representing the most pessimistic market conditions.

Additional benefits: Beyond the economic benefits from the collective use of oil stocks quantified in this study, individual countries can gain additional value from holding stocks. Stocks can be used to address local or domestic petroleum disruptions that may be too small or localised to trigger the use of collective IEA stocks. They can enhance a country's diplomatic flexibility by at least partially diminishing the oil import security imperative as a foreign policy constraint. Similarly, they can improve national security by diminishing the need for military forces to help protect oil supply and transit, and by assuring petroleum supply for national defence operations during emergencies. Policy makers have consistently indicated the non-economic benefits of reducing political, military and economic vulnerability to oil market events. To the extent that oil stocks reduce the cost of market shocks, natural disasters or any other interruption in supply, they provide greater independence and reduce costs in non-economic spheres as well.

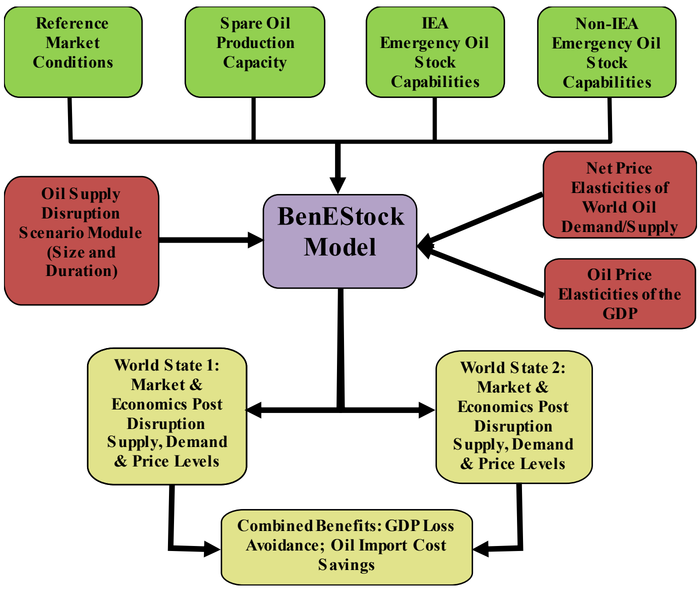
Annex 1: BenEStock model and inputs for the IEA stock study[33]

A1.1 BenEStock model overview

The economic benefits of global oil stocks are simulated with an updated version of ORNL's BenEStock model (see Leiby et al., 2016, for details). BenEStock allows for the analysis of specific risk-related outcomes in a simulation or scenario-driven format. Emergency stocks are characterised in terms of draw rate capabilities, stock sizes and fill/refill rates. The model can be used to look at individual disruption scenarios, or run in a Monte Carlo risk analysis fashion to produce estimates of the expected benefit, expected frequency of disruptions and use of emergency stocks, the probability of stock exhaustions, and the probability distribution of economic benefits. The model produces estimates of the expected (or average) economic benefits and the probability distribution of economic benefits. The Monte Carlo analysis also produces the expected frequency of disruptions and use of emergency stocks, and the probability of stock exhaustions.

The key inputs for estimating the economic benefits of stockholding with BenEStock are illustrated in the green and red boxes of Figure A1-1.

Figure A1-1 • Flow diagram of the BenEStock model



Outputs from the model, including supply, demand, prices and GDP levels, are shown in the yellow boxes of Figure A1-1. Two world states are simulated side by side (for example, one state could be the use of IEA emergency stocks and the other state, without use of emergency stocks) and consumption levels, production levels, prices, etc. are calculated for each state, resulting in net benefits or costs of policies or options. A comparison of the GDP losses and cost of oil imports between the scenarios then yields the value of global emergency stocks.

[33] The material in this annex drawn from Leiby et al. (2018).

A1.2 BenEStock inputs for the IEA study

The six key inputs into the BenEStock model are described below:

- reference market conditions (undisrupted market prices and regional supplies, demands, GDPs and spare oil production capacity)
- oil supply disruption likelihoods (based on supply regions at risk, the anticipated sizes, durations and probabilities of supply loss)
- spare oil production capacity (Saudi Arabia and Other Persian Gulf)
- emergency oil stock capabilities (stock size, draw capabilities and availability)
- market responsiveness to shocks (demand/supply elasticities)
- macroeconomic sensitivity to shocks (GDP elasticities).

Details of these inputs are discussed in Leiby et al. (2016), Uria-Martinez et al. (2018) and Oladosu et al. (2018). The following discussion of the six key inputs is based on these documents, but has been updated to reflect the specifics for this study as needed. Annex 2 is a full list of assumptions used for the study based on extensive discussions with IEA staff and member SEQ representatives.

A1.2.1 Reference market conditions

In the BenEStock model, reference oil market conditions are used to determine the undisrupted market state that is used as a point of departure for potentially disrupted markets. Net imports (demand minus supply) and GDP are used to determine the magnitude of economic costs. Where available, reference oil market conditions are drawn from the IEA *WEO* New Policies Scenario. Reference market data include:

- GDP (billion USD 2016) from *WEO 2017*. When necessary, forecasts for individual countries and groups not given in the *WEO* are estimated using year 2017 GDP shares from the International Monetary Fund (IMF) *World Economic Outlook, October 2017*.
- World oil price: average IEA crude oil import price (USD 2016/bbl) from *WEO 2017*.
- World oil demand: total primary oil demand (including bunkers, mb/d) from *WEO 2017*.
- Regional oil demand: total primary oil demand from *WEO 2017*. When necessary, forecasts for individual countries and groups not given in the *WEO* are estimated using year 2015 demand shares from the EIA's International Energy Statistics.
- Regional oil production by net importing countries: oil production plus process gains from *WEO 2017*. When necessary, forecasts for individual countries and groups not given in the *WEO* using year 2015 production shares from the EIA's International Energy Statistics.
- Saudi Arabia, Other OPEC, and West of Suez OPEC Oil Production: *WEO 2017*.
- Russia and Caspian Region Oil Production: Russia and Kazakhstan taken directly from the *WEO 2017*. Azerbaijan and Turkmenistan estimated using *WEO 2017* and using year 2015 production shares from the EIA's International Energy Statistics.

A1.2.2 Disruption likelihoods

Characterisation of the risk of net supply shortfalls is composed of two parts: the specification of the probability of gross (before offset) shortfalls and the specification of the availability of spare production capacity to offset the disruption. World oil supply disruptions in BenEStock are characterised by their magnitude and duration. Naturally, these likelihoods are difficult to assess.

Disruption likelihoods are based on the 2015 EMF assessment, which may be compared with an ever-lengthening history of oil market disruption events.

The EMF 2015 Expert Panel study quantified oil disruption risks over the course of two rounds of workshops in 2015. These workshops constituted a formal risk assessment using the methodologies of decision analysis and influence diagrams. The focus was on potential losses of supply from five key regions plus the Strait of Hormuz choke point:

- Saudi Arabia
- Other Persian Gulf
- OPEC Africa
- Latin America (Venezuela, Mexico and Brazil)
- Russia and Caspian Region
- Strait of Hormuz.[34]

The gross disruption (prior to offsets) probability assessment was based on the assessment of conditional event sequences that can lead to supply losses; that is, some supplier groups' outcomes can depend conditionally on other supplier outcomes. The assessment also explicitly considers disruption duration along with size probability, so that there are conditional disruption size probabilities for each disruption length. Three disruption lengths were considered in the expert elicitation discussed: "short" (1-6 months), "long" (6-18 months) and "very long" (>18 months).[35] For the current simulations, these three ranges are represented with three distinct discrete lengths, being 3, 12 and 18 months. The first two are essentially the midpoints of the respective ranges. For the third, longest range of events, 18 months is used, which was consistent with the "very long" duration used in previous studies based on the EMF 2005 assessment.[36]

The EMF-led expert assessment concluded that disruption risk, at least in some regions, may vary with the future oil price path. Lower prices were assumed to entail somewhat more risk of supplier instability than more moderate price paths. The assessment also considered spare capacity, the availability and likelihood of which uses a separate distribution. The focus of the EMF assessment was disruption risk for the next decade. For the purposes of BenEStock longer-term analysis, these same risk probabilities (annualised) are maintained in terms of *percentage* supply shortfalls by region throughout the horizon of analysis. Information from the EIA *Annual Energy Outlook* is used to project the evolving reference supply from each of the regions at risk.

The BenEStock disruption risk characterisation includes:

- Five supply regions at risk corresponding to the EMF 2015 focus regions (Saudi Arabia, Other Persian Gulf,[37] Africa,[38] Latin America,[39] and Russia and Caspian region[40]), plus the Straits of Hormuz as a choke point.

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[34] The Strait of Hormuz is not a supply region, but a potential choke point that can restrict supply from two regions, Saudi Arabia and Other Persian Gulf. To avoid double counting, if the percent disrupted of either Saudi Arabia or Other Persian Gulf is greater than 50% then the percent disrupted of Strait of Hormuz is automatically zero.

[35] Note that the ranges overlap at the boundaries, and there was no attempt to specify distribution of lengths within these ranges. That sort of resolution perhaps would not have been achievable or appropriate to pursue.

[36] The simulations by Beccue and Huntington (2016) use 6, 12 and 24 months to represent the three ranges.

[37] In this report, Other Persian Gulf includes Iran, Iraq, Kuwait, Qatar, the United Arab Emirates and Oman.

[38] In this report, Africa refers to OPEC Africa: Algeria, Angola, Libya and Nigeria.

[39] In this report, Latin America refers to Brazil, Mexico and Venezuela.

[40] In this report, Russia and Caspian Region refers to Azerbaijan, Kazakhstan, Russia, Turkmenistan and Uzbekistan.

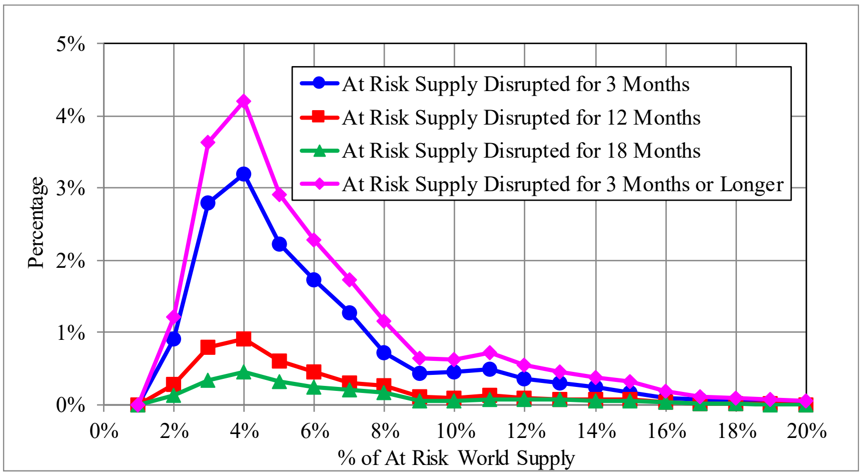
- Three disruption lengths (taken as 3, 12 and 18 months), not equally probable.
- EMF 2015 discrete disruption probabilities by size (as percentage of supply), distinct for each region and conditional on disruption length.
- Uniform distribution of +/-10% around the discrete EMF disruption size. Converts the disruption probabilities from discrete to semi-continuous, avoiding issues with arbitrarily missing threshold boundaries while maintaining the EMF expected values.
- Separate, independent EMF 2015 probability distributions for the available volume of excess production capacity from Saudi Arabia and Other Persian Gulf.

To reflect that disruption risk might rise or fall as supply becomes more or less concentrated in volatile regions, disruption sizes are specified as percentage losses of supply from various regions. These are shown in Table A1-1 below.

Looking at the table, the most likely single event is a relatively small three-month production loss from OPEC Africa (4.21% annual probability) followed by an equally short disruption in Russia and Caspian Region (3.48% annual probability). A "worst-case scenario" of up to 90% of production being disrupted is conceivable only in Saudi Arabia (0.017% annual probability, 5% probability over 30 years) and Russia (0.05% annual, 1.5% over 30 years). Overall, the least likely event is a loss (of any duration) resulting from a Strait of Hormuz disruption (1.03% annual probability) followed by a disruption of any duration in Latin America (2.02% annual probability). Combinations of semi-continuous, independent EMF-based regional probabilities allow for an unlimited number of possible market states of various sizes and lengths. However, as expected, of the multiple outcomes, 0% production loss in all of the regions is the most common, occurring approximately 78% of the time.[41]

Figure A1-2 shows the annual probability averaged across at-risk regions and across the time horizon. These probabilities are of a given percent of at-risk supply for a given length of time.

Figure A1-2 • Distribution of annual at-risk production disrupted



[41] If each of the annual probabilities is independent, then the probability of no outcome is 76%; however, in the benefit model's (BenEStock's) annualised treatment, for each region and for each year, there are no disruptions if in the same region there was disruption greater than 12 months in the previous year. Similarly, if either Saudi Arabia or Other Persian Gulf is disrupted by greater than or equal to 50%, there is no additional disruption in the Strait of Hormuz. As such the annual probability used in the model is 78%.

As the figure shows, the most likely single outcome is a disruption of approximately 3% of at-risk supply (2 mb/d to 3 mb/d depending upon the year) lasting three months. In all, the likelihood of an approximate 4% loss for three months or greater is 4%.

Table A1-1 • EMF 2015 annual independent discrete disruption probabilities for base price case

Saudi Arabia				
Size/Length	**0% of production**	**20% of production**	**50% of production**	**90% of production**
3 months	38.88%	2.28%	0.36%	0.09%
12 months	27.84%	0.82%	0.19%	0.05%
18 months	29.01%	0.34%	0.12%	0.03%
Any length	95.72%	3.44%	0.67%	0.17%
Other Persian Gulf				
Size/Length	**0% of production**	**20% of production**	**50% of production**	**90% of production**
3 months	27.85%	2.39%	0.46%	0.00%
12 months	26.87%	1.28%	0.35%	0.00%
18 months	39.61%	0.86%	0.32%	0.00%
Any length	94.33%	4.53%	1.14%	0.01%
OPEC Africa				
Size/Length	**0% of production**	**20% of production**	**50% of production**	**90% of production**
3 months	38.56%	4.21%	0.24%	0.00%
12 months	26.75%	1.22%	0.13%	0.00%
18 months	28.31%	0.51%	0.09%	0.00%
Any length	93.62%	5.93%	0.45%	0.00%
Latin America				
Size/Length	**0% of production**	**20% of production**	**50% of production**	**90% of production**
3 months	57.51%	1.17%	0.42%	0.00%
12 months	21.60%	0.20%	0.11%	0.00%
18 months	18.88%	0.07%	0.05%	0.00%
Any length	97.98%	1.44%	0.58%	0.00%
Russia and Caspian Region				
Size/Length	**0% of production**	**20% of production**	**50% of production**	**90% of production**
3 months	84.81%	3.48%	0.75%	0.05%
12 months	8.53%	0.04%	0.02%	0.00%
18 months	2.30%	0.00%	0.00%	0.00%
Any length	95.64%	3.53%	0.77%	0.05%
Strait of Hormuz choke point				
Size/Length	**0% of production**	**15% of production**	**50% of production**	**90% of production**
3 months	73.25%	0.81%	0.14%	0.00%
12 months	25.71%	0.06%	0.02%	0.00%
18 months	0.00%	0.00%	0.00%	0.00%
Any length	98.97%	0.87%	0.16%	0.00%

A1.2.3 Spare oil production capacity

In BenEStock, one of the response mechanisms to an oil supply disruption is output increases by other producers with spare capacity. The spare capacity considered in this study is restricted to OPEC countries. Within the cartel, two different subregions are considered (Saudi Arabia and Other Persian Gulf). Based upon conversations with Saudi Aramco and the definition of spare capacity data, as a base case, spare capacity in BenEStock is available for drawdown three months after the initial disruption. Probabilistic estimates for the available volume of spare capacity are from the EMF 2015 study. These are given in Table A1-2.

Table A1-2 • Available spare capacity and its likelihood from EMF 2015*

Saudi Arabia	
Size (mb/d)	**Probability**
0.0	25%
0.5	5%
1.0	25%
1.5	25%
2.0	20%
Other Persian Gulf OPEC	
Size (mb/d)	**Probability**
0.0	85%
0.5	15%

*Spare capacity is not available if the source region is disrupted.

Source: Beccue and Huntington (Energy Modeling Forum) (2016).

The EMF study group results indicate an effective spare capacity in Saudi Arabia of up to 2 mb/d. This is consistent with other long-term forecast values cited elsewhere.[42] In addition to the probabilistic availability of excess capacity, it is also assumed that excess capacity is not available in disrupted regions.

A1.2.4 Emergency oil stock sizes and availability

IEA countries holding emergency oil stocks are assumed to engage in collective withdrawal action when spare production capacity is not enough to offset simulated supply disruptions to an acceptable level. More specifically, the net supply loss (after offsets, such as production from spare capacity and demand response) must be above the drawdown threshold, which is 2 mb/d in the base case for this study, to trigger emergency stock releases.

IEA emergency stockholdings

Initial IEA stocks are based on data from IEA. Projected emergency stock levels in the future are assumed to adjust with imports and consumption levels, in accordance with current laws of member countries, as summarised in Table A1-3. Projected levels of publicly-controlled stocks and obligated private industry stocks are estimated using legislative information provided by various IEA documents. If no information concerning future levels is available, stock levels are

[42] E.g. US EIA (2011), "Saudi Arabia will continue with its current plan to maintain spare production capacity at levels between 1.5 and 2.0 million barrels per day." (US EIA, 2011: 35).

held constant throughout the model horizon. Table A1-3 contains detailed information on legislated public and private emergency stockholdings for each country.

Table A1-3 • Legislated requirements for IEA public and private emergency stockholdings

Country	Public stock estimate	Obligated private stock estimate
Austria	98% of obligated private stocks (22 mb in 2015) delegated from obligated private stocks	100 days of oil imports of three EU product categories. 2% currently privately held, rest delegated to public storage.
Belgium	28 mb starting value. Max of the EU and IEA commitments.	0 mb (no obligation)
Czech Republic	16 mb starting value. Max of EU and IEA commitments.	0 mb (no obligation)
Denmark	70% of obligated private stocks (7 mb in 2015) delegated from obligated private stocks	81 days' consumption of inland consumption. 70% held by stockholding association (public stock).
Finland	21 mb in 2015. Max of EU and IEA commitments not covered by obligated industry stocks.	60 days of net imports
France	75% of obligated private stocks (110 mb in 2015) held as public stocks	29.5% of the volume of oil released for domestic consumption during the previous calendar year
Germany	186 mb in 2015. Max of EU and IEA commitments, no industry stocks.	0 mb (no industry-held stocks)
Greece	0 mb	Industry obligation of 90 days of net imports of three EU product categories
Hungary	9 mb in 2015. Max of EU and IEA commitments	0 mb (no obligation)
Ireland	13 mb in 2015. Max of EU and IEA commitments	0 mb (no obligation)
Italy	2 mb in 2015	Max of IEA and EU commitments
Luxembourg	0 mb	Max of IEA and EU commitments
Netherlands	22 mb in 2015. Max of EU and IEA commitments not covered by obligated industry stocks.	12% of volumes released to inland market for companies releasing more than 100 000 tones (gasoline, gasoil/diesel, jet kerosene)
Norway	0 mb	20 days of oil domestic consumption of three EU product categories.
Poland	12 mb in 2015. Max of EU and IEA commitments not covered by obligated industry stocks.	61 days of net imports changing to 53 days by 2018
Portugal	8 mb in 2015. Max of EU and IEA commitments equal to 1/3 of the total.	Max of IEA and EU commitments. Industry obligations equal to 2/3 of total.
Slovakia	6 mb in 2015. Max of EU and IEA commitments.	0 mb (no obligation)
Spain	51 mb in 2015. Max of EU and IEA commitments, 45/55 public/private split.	Max of EU and IEA commitments, 45/55 public/private split
Sweden	0 mb	Max of IEA and EU commitments
Switzerland	0 mb	135 days of imports for gasoline, diesel and heating oils; 90 days of jet fuel imports
Turkey	0 mb	Refineries are obliged to hold stocks equivalent to 20 days' worth of their previous year's supply. Fuel and liquefied petroleum gas distribution licensees are obliged to hold product stocks equivalent to 20 days' worth of average daily sales of the previous year.

Country	Public stock estimate	Obligated private stock estimate
United Kingdom	0 mb	Max of EU 67.5 days of supply for refineries and 58 days of net imports for importers, and IEA 90-day import commitment.
Australia	0 mb	0 mb (no obligation)
Canada	0 mb	0 mb (no obligation)
Japan	324 mb in 2015	250 mb in 2015
Korea	93 mb in 2015. Balance of IEA commitments not covered by obligated industry stocks.	40 days of consumption
New Zealand	2 mb	0 mb (no obligation)
United States	695 mb	0 mb (no obligation)

Projected estimates of IEA and non-IEA emergency stocks are summarised in Figures A1-3 and A1-4. For the IEA, these estimates are based on the legislative requirements discussed above and use country-level consumption and net import forecasts from the EIA *Annual Energy Outlook*, where available. When country-level forecasts were not available, estimates were derived using country group forecasts and year 2015 country shares from the EIA International Energy Statistics tables.

Figure A1-3 • IEA and non-IEA emergency oil stocks (end of year, mb)

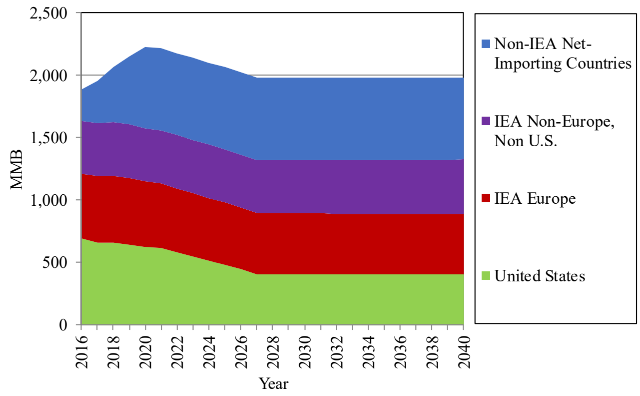
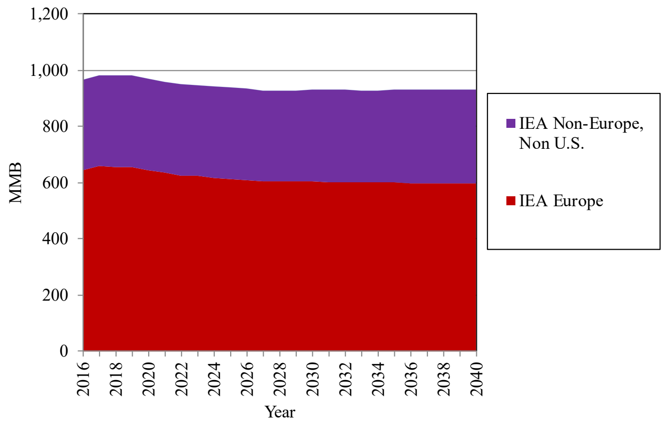


Figure A1-4 • IEA mandated industry oil stocks (end of year, mb)



Non-IEA emergency stockholdings

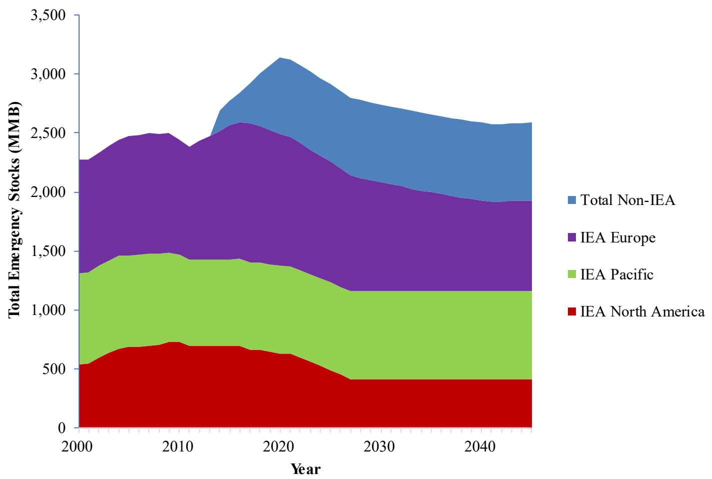
Estimates for non-IEA emergency stock, based on information provided by the IEA, are presented in Table A1-4.

Table A1-4 • Non-IEA emergency stock estimates by 2021

Country	Storage (mb)
China	500
India	113
Indonesia	45
Total	658

Combining the different categories discussed in this section yields the total world emergency stockholdings displayed in Figure A1-5.

Figure A1-5 • Total emergency stocks (end of year, mb)



Stock availability

Under base assumptions, all IEA public and obligated private stocks are assumed to be always available. There is considerable uncertainty as to whether or not non-IEA stockholders would draw down in the absence of agreements with the IEA. As a base case, non-IEA stocks are assumed to be unavailable (i.e. 0% availability). Sensitivity cases are simulated with 50% and 100% non-IEA stock availability. When available, non-IEA stocks are assumed to be used simultaneously with IEA stocks in all events.

Emergency oil stock drawdown rates

For this study, except in selected sensitivity cases, the results presented apply a drawdown threshold so that not all disruptions lead to stock draw. The drawdown threshold value is 2 mb/d net shortfall in the base case, and variants are considered. The drawdown strategy, once the threshold is exceeded, is to initially draw at maximum draw rate necessary to fully offset the net shortfall, up to the maximum technically feasible rate, for the first three months. After three months, if the disruption persists, drawdown slows to the maximum sustainable rate for the expected duration of disruption. The "sustainable" draw rate is the highest rate that can be sustained for the remainder of the disruption, given available stocks.

A set of technical maximum drawdown rates is estimated using functions fitted to data on the actual maximum draw rate as a function of remaining stock. This approach was used to accurately describe the time-dependent drawdown capabilities available over the course of a disruption.

Table A1-5 displays maximum drawdown rates for IEA Europe and IEA Asia and Pacific indexed by drawdown week, as provided by IEA to ORNL.

Table A1-5 • Maximum drawdown rates indexed by drawdown week (kb/d)

	IEA Europe	IEA Asia and Pacific
Week 3	7,114	6,135
Week 4	6,492	5,199
Week 5	5,834	3,861
Week 6	4,812	3,606
Week 7	4,397	3,491
Week 8	3,694	2,996
Week 9	3,269	2,781
Week 10	3,051	2,597
Week 11	2,946	2,417
Week 12	2,878	2,040
Week 13	2,728	2,040
Week 14	2,283	1,842
Week 15	1,559	1,339
Week 16	1,559	1,132
Week 17	1,559	1,132
Week 18	1,484	845
Week 19	1,482	674
Week 20	1,482	306
Week 21	1,482	261
Week 22	1,449	261
Week 23	1,032	261
Week 24	362	243
Week 25	219	207
Week 26	219	207

Source: IEA databse, 2012

In addition, US SPR daily drawdown rates for various configurations were provided to ORNL by the US DOE.

Excluding the initial start-up, the daily and weekly draw rates are converted to monthly rolling average draw rates by size (BenEStock is a monthly model). The constrained technical maximum draw rate for each region's stocks is fit to a tenth order polynomial function and subject to logical constraints. This functional form was chosen because of its generality and ability to fit the irregular drawdown rate data well.

The fitted constrained technical maximum draw (CTMD) rate function is

$$CTMD = (aX^{10} + bX^{9} + cX^{8} + dX^{7} + eX^{6} + fX^{5} + gX^{4} + hX^{3} + iX^{2} + jX + k) + (6\ Month\ Exhaustion\ Rate * exhaustion\ multiplier)$$

where $X = Min(StockSize, Year\ 2010\ Size)$

Draw rates conform to the stock sizes available in year 2010 and no increase in draw capacity for sizes greater than that in year 2010 is assumed.

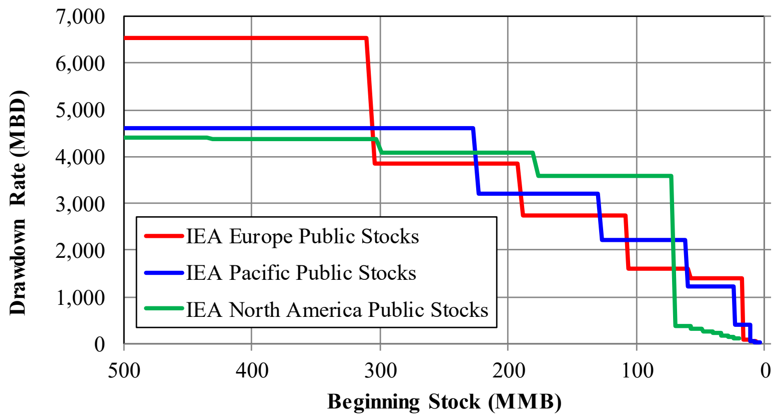
Parameters *a* through *k* are derived by fitting tenth order polynomial to data points for draw weeks 2-26. The typical R squared was 98-99%. Since no draw profile is available for non-IEA net importing countries, parameter values for those countries were assumed to be zero.

Exhaustion multiplier = 1 for non-IEA net-importing group (0 for everyone else) with 0 values for polynomial parameters. Therefore, draw rate for non-IEA net-importing group is the *6-Month Exhaustion Rate* subject to:

$$0 \leq CTMD \leq Technical\ Maximum\ Rate$$

In addition to the upper and lower bounds placed upon drawdown rates, a first-month draw rate limitation is also applied to account for the slower drawdown capability in the initial weeks for some regions. For the first few weeks, drawdown capabilities are limited by start-up lags. After one week, the technical drawdown capability peaks. Subsequently, the underlying relationship between the maximum drawdown capability and remaining stock size becomes apparent. Regional comparisons of the estimated technical maximum drawdown rates (ignoring first-month start-up reduction) used in the model are provided in Figure A1-6.[43]

Figure A1-6 • IEA public stock max monthly draw rate for corresponding month beginning size



[43] Although there could be an immediate market effect following an IEA stock draw announcement, or even in anticipation of such an announcement, the first-month price response in the benefits model is based on actual quantities drawn and their relationship to supplies and demands. Note that the IEA decision to authorise and announce a stock draw is not immediate, so the initial one week built into BenEStock may also capture initial uncertainty about the necessity for and decision to release IEA stocks.

This chart excludes the initial-month draw reduction. The US SPR draw rate shown corresponds to a 695 mb size; the draw rate profile changes over time as the US SPR reserves are drawn down to 415 mb by 2027.[44]

A1.2.5 Market responsiveness: Supply elasticities

Crude oil supply is generally assumed to be the same for the disrupted and non-disrupted cases in this study, except for the following two adjustments: 1) spare capacity in OPEC countries; and 2) tight oil supply in the United States. Assumptions regarding spare oil production capacity in OPEC countries, specifically Saudi Arabia and Other Persian Gulf, are outlined in section A1.2.3.

US tight oil production represents a small share of global liquid fuel supply at about 5% (about 5 mb/d) in 2018, projected to grow to 7% (nearly 8 mb/d) by 2030. US tight oil supply is price responsive in the simulations for this study, using supply elasticities that were estimated from a preliminary econometric model.[45] Although the tight oil supply estimates are preliminary, data are limited and research into the economics of tight oil is relatively new, a few recent studies have provided additional evidence on the response of US tight oil production to oil price changes. Most of these studies reach a similar conclusion to this report's, finding that unconventional oil is price inelastic in the short to medium term. Newell and Prest (2017) estimated the price responsiveness of drilling, spud-to-production and production from existing wells for US oil production. They found that while drilling activity is highly price responsive, the latter two stages of tight oil production are inelastic with respect to price. Their estimated supply elasticities for oil production from existing wells are 0.12 for unconventional wells and 0.02 for conventional ones. Based on the model specification, these estimates are long-run in nature, and the 0.12 estimate for tight oil supply from Newell and Prest is about half of the model's 0.223 long-run estimate. Given that the lag between drilling and completion of a well can be many months, they also conclude that "it takes many months before a substantial portion of the full supply response is online, longer than the 30 to 90 days typically associated with the role of 'swing producer' such as Saudi Arabia."

Kleinberg et al. (2017) examined the different stages of tight oil production and the corresponding break-even prices that are used to guide industry decisions, concluding that "U.S. tight oil production does not ramp up or down quickly enough to significantly affect short term oil market stability. However, it does have the potential to stabilise oil markets in the medium term."

Montgomery and O'Sullivan (2017) examined the relative contributions of location and technology to tight oil well productivity in the US Williston Basin using detailed well data and accounting for high-resolution spatial dependence.[46] They concluded that future tight oil supply response may be more limited than some estimate because much of the recent supply gains stem from focusing development in the most productive and profitable known areas of an established basin (so called "high-grading") rather than from technology improvements.

[44] Although it is possible to model different configurations of the US SPR, the simulations in this study are based on a proportional reduction in the size of all four SPR locations. The decision and locations of any sites that could be closed is pending.

[45] A panel autoregressive distributed lag (ARDL) model of monthly oil production is fetted to rig count and the price of WTI oil using data for seven US tight oil producing regions. The resulting model provides estimates of both short- and long-run supply elasticities of tight oil in the United States. The short-run supply elasticity estimate is 0.024 and the long-run supply elasticity is 0.223. For the BenEStock simulations, the short-run estimate is applied to the first month of a disruption, and interpolated between the short- and long-run supply elasticities linearly over 24 months.

[46] The US portion of the Williston Basin covers parts of Montana, North Dakota and South Dakota.

Specifically, they find that the impact from high-grading of drilling locations in the Williston Basin on well productivity has been roughly equivalent to the impact of technology. This means that, all else equal, well productivity gains could be significantly lower as future US tight oil production expands beyond existing geological sweet spots. Although these results are specific to the studied basin, they would likely be applicable to other basins due to similar high-grading practices. Thus, forecasts expecting tight oil productivity gains similar to those observed during the past few years may overestimate future tight oil supply in the United States.

A1.2.6 Market responsiveness: Demand elasticities

Oil demand and supply elasticities determine the degree to which oil supply shocks (shortfalls) translate into oil price increases. The smaller the elasticity (in absolute terms), the greater the price increase, but behaviour at very high prices is poorly understood.[47] Most of the assessments of elasticity that can be found in the literature refer to annual periods. However, disruption analysis typically calls for modelling quarterly or, in the case of BenEStock, even monthly response. It is widely accepted that short-run demand and supply elasticities with respect to price are quite small, while longer-run elasticities, which may apply after a number of years, are four to ten times larger. Furthermore, studies usually estimate a single (constant) elasticity regardless of the magnitude of price increase, which is problematic because such elasticities imply extremely high short-run prices for large disruptions.

Given the above, a variable elasticity was applied for the market response to changing prices in line with prior emergency stock studies (DOE, 1990; APERC; 2000; Leiby and Bowman, 1999, 2005, 2007; IEA, 2013; Leiby et al., 2015). Apart from comparability to prior emergency oil stock studies, this approach has the primary advantage that demand elasticities increase over the course of a disruption (reflecting the process of slowly increasing adjustment over time to sudden price changes) and they also increase with the magnitude of the disruption supply shortfall. The resulting elasticities grow with the magnitude of supply shortfall, and prevent prices from becoming arbitrarily large for very large disruptions, as would occur with a fixed short-run elasticity.

The ordinary elasticity of demand accounts for both a substitution and an income effect, with the income effect representing the immediate change in purchasing power experienced by oil consumers. In addition, an extra income effect term is included that captures the second-order effects on demand responsiveness to an oil price change due to the effect of the oil price shock on GDP. Using a constant elasticity functional form, referring to the demand elasticity with respect to price and income as $\varepsilon_{d,P}$ and $\varepsilon_{d,Y}$, respectively, and to the elasticity of GDP with respect to price as $\varepsilon_{Y,P}$, the total demand elasticity with respect to price (including direct price effect and indirect income effect) is:

$$\frac{\partial D(P,Y)}{\partial P} * \frac{P}{D} = \varepsilon_{d,P+}\varepsilon_{Y,P} * \varepsilon_{d,Y}$$

The functional form for demand elasticity used in this study includes five additive terms: 1) intercept, representing the base or short-run demand elasticity; 2) month after disruption; 3) disruption shortfall size; 4) interaction of month and disruption shortfall size; and 5) second-order income effect (i.e. the second term on the right-hand side of the above equation).

[47] For example, a short-run (annual) net demand response elasticity of -0.10 would imply that a 20% loss of supply would increase price by over ninefold (to above USD 900) for the first year.

$$\epsilon_D(\Delta, t, m) = \alpha(t) + \beta(t) * m + \gamma(t) * \Delta_{sf}(t, m) + \lambda(t) * m * \Delta_{sf}(t) + \iota(t) * \varepsilon_{GDP}(t)$$

$$\eta_S(t, m) = \eta_0(t) + \eta_1(t) * m$$

$$\epsilon_N(\Delta, t, m) = \frac{D_t^{elastic}}{(D_t^{elastic} - S_t^{elastic})} * \epsilon_D(\Delta, t, m) - \frac{S_t^{elastic}}{(D_t^{elastic} - S_t^{elastic})} * \eta_S(t, m)$$

where ϵ_D is the elasticity of demand, η_S is the elasticity of supply, m is number of months since the start of the disruption, Δ_{sf} is oil shortfall volume, $D_t^{elastic}$ is elastic demand, $S_t^{elastic}$ is elastic supply (US tight oil supply) and ϵ_N is the net demand elasticity.

The elasticity of GDP in the second-order income effect is from a recent ORNL meta-analysis of the oil price elasticity of GDP described in more detail at the beginning of this section. (Oladosu et al., 2018). The intercept term (α[t]), and the coefficient on the number of months after disruption term (β[t]), as well as the income elasticity used to calculate the second-order income effect (ι[t]) in the demand elasticity equation are from a recent ORNL meta-analysis of the price and income elasticities of oil demand (Uría-Martínez et al., 2017).[48] Table A1-6 displays short- and long-run elasticities with respect to price and income in two sectors (transportation and non-transportation) and two regions (OECD and non-OECD) obtained from the meta-regression estimated coefficients.[49] It also contains the mean length of run for the samples of elasticities used as inputs in the meta-regressions.

Table A1-6 • Values from ORNL demand elasticity meta-analysis used to derive linear relationship between elasticity and number of months since disruption

Elasticity attributes	Mean value	Standard error	Mean length of run (years)
Short-run price elasticity, OECD, transportation	-0.0764	0.0320	0.8033
Short-run price elasticity, OECD, non-transportation	-0.0667	0.0190	1.0000
Short-run price elasticity, non-OECD, transportation	-0.0884	0.0234	0.9134
Short-run price elasticity, non-OECD, non-transportation	-0.0441	0.0152	0.9756
Long-run price elasticity, OECD, transportation	-0.1578	0.1249	10.0121
Long-run price elasticity, OECD, non-transportation	-0.3675	0.1125	23.8336
Long-run price elasticity, non-OECD, transportation	-0.2344	0.1028	8.0837
Long-run price elasticity, non-OECD, non-transportation	-0.2788	0.0820	7.0823
Short-run income elasticity, OECD, transportation	0.1661	0.0436	0.8337
Short-run income elasticity, OECD, non-transportation	0.0690	0.0734	1.0000
Short-run income elasticity, non-OECD, transportation	0.2557	0.0390	0.8973
Short-run income elasticity, non-OECD, non-transportation	0.0462	0.0676	0.9784
Long-run income elasticity, OECD, transportation	0.7136	0.0765	17.4424
Long-run income elasticity, OECD, non-transportation	0.6490	0.0848	12.2327
Long-run income elasticity, non-OECD, transportation	0.8624	0.0690	7.7615
Long-run income elasticity, non-OECD, non-transportation	0.7540	0.0665	6.0209

[48] See US EIA (2002) and GAO (2006).

[49] No separate meta-regressions were conducted for OECD and non-OECD data. The regional elasticity values result from evaluating the meta-regression estimated coefficients at the regional means of several moderator variables and including or excluding the effect of an OECD indicator variable.

Each pair of short-run and long-run elasticities and their respective mean length of runs provide two points in the relationship between elasticity and length of run. Intercept (α) and slopes (β) for eight elasticity-length of run curves are computed assuming that the relationship is linear. Standard errors for the intercept and slope coefficients are also computed based on error propagation rules. The α (t), β (t), and ι (t) used in the demand elasticity equation are the consumption-weighted averages of their values for individual region-sector combination.[50] The consumption weights are taken from EIA *International Energy Outlook* projections. Since these weights vary by year, α (t), β (t), and ι (t) are also indexed by time period.

To estimate price impacts during an oil supply shock, net elasticity of demand and supply for the entire world are needed, since oil price is determined globally. The world net demand (demand minus supply) elasticity for a given year, supply shortfall size, and time elapsed from the start of the disruption (ϵ_N) are calculated as the weighted sum of demand and supply elasticities, where the weights are the ratio of demand and supply to the net demand. The supply elasticity (η_s[t,m]) is a preliminary statistical estimate for US tight oil supply estimated by ORNL. Table A1-7 shows the world net demand elasticity (ϵ_N) average values for 0 mb/d and 10 mb/d disruption shortfalls for 2025.

Table A1-7 • Year 2025 average world net demand elasticities for various months and shortfall levels

Oil shortfall	0 mb/d	10 mb/d
Elasticity after 1 month	-0.06	-0.11
Elasticity after 12 months	-0.07	-0.15
Average elasticity over 12 months	-0.07	-0.13

A1.2.7 Macroeconomic sensitivity to oil price shocks

Estimates of the GDP impact of oil shocks in the BenEStock model involve a direct reduced-form relationship between price implications and the GDP. This approach can be described as a summary of different approaches for modelling the macroeconomic effects of the oil supply shocks in the literature, accounting for the direct and indirect effects on the economy. Depending on the application, BenEStock can track economic effects to four global groups of oil-importing economies: the United States, IEA Europe, Other IEA, and Non-IEA. The change in regional GDP (RGDP) associated with an oil supply disruption, ΔRGDP, is calculated based on the estimated change in oil prices, ΔP, as:

$$\Delta RGDP(t) = RGDP_{ref}\left[\left(1+\frac{\Delta P(t)}{P_{ref}}\right)^{\varepsilon_{GDP}}-1\right]$$

The above equation requires estimates of the oil price elasticity of the GDP, ε_{GDP}, reference RGDP(t) and oil price, $RGDP_{ref}$ and P_{ref}, and the price change due to the oil disruption event, ΔP(t). Estimates of the oil price elasticity of the GDP are based on a meta-regression analysis of the literature presented in Oladosu et al. (2018) is provided below. The meta-regression analysis was performed by fitting a linear regression (meta-regression) to data collected from 19 recent studies, with the US and European economies accounting for 90% of the estimates. The meta-regression model

[50] The input from the demand elasticity meta-analysis to the BenEStock Monte Carlo analysis includes 20 000 random draws of the intercepts of the eight elasticity-length of run relationships. For each of them, the draws are taken from normal distributions truncated at +/-1 standard deviations of the mean intercept value. The slopes of the elasticity-length of run relationships are not treated as random variables in the BenEStock Monte Carlo analysis.

accounted for important sources of heterogeneity in estimates of the oil price elasticity of the GDP across studies, including size of the oil price shock, measures of the time elapsed since the shock, regional economic variables (GDP per capita, and ratios of petroleum consumption and import to energy consumption), dummy variables to represent the modelling approach underlying study estimates (macro-econometric, vector auto-regression and general equilibrium models), dummy variables for the period covered by the data in five-year intervals, and dummies for key regions to capture other variations not explained by the remaining variables.

For the current study, the meta-regression model estimated in Oladosu et al. (2018) was simulated to calculate quarterly elasticities for 142 net oil importing countries, plus the euro area as a single region. Data for region-specific variables in the model, including per capita GDP, petroleum share of energy use and net petroleum imports share of energy use for 2005 and regional dummies, were varied for this purpose. Year 2005 is the same year used for these variables in the cross-sectional meta-regression model. The Monte Carlo simulation for each country consisted of 250 000 replications. However, random variations in the model coefficients and non-regional variables were kept the same for each regional simulation. In addition, regional dummy variables in the meta-regression model are limited to the United States (baseline region), Australia, the euro area, Europe (countries), the United Kingdom, Germany, sub-Saharan Africa, Japan, China and India. For any of the 142 regions that could not be assigned to one of these regions, the Australia dummy was used, because its coefficient estimate is very close to the average of all regional dummy coefficients. The 250 000 replications were used to estimate the mean GDP elasticity, as well as 68% confidence intervals for each of the 142 countries and the euro area.

The 142 countries were mapped to the four regions in this study, i.e. IEA North America, IEA Europe, Other IEA and Non-IEA. A weighted average of the mean and 68% confidence intervals of the individual GDP elasticities were then calculated using projected 2010-30 annual real GDP estimates from the *Economic Research Service* (ERS, 2016) as weights. Results show that there is only a negligible amount of variation in the weighted regional GDP elasticities across years, suggesting that the relative GDP position of each country within regions would vary very little over time.

Although there is some variation in the elasticities over quarters following a shock, a single set of GDP elasticities estimates for the fourth quarter after a shock is adopted for the current study. In addition, the GPD elasticity used for IEA Europe is the value estimated for the euro area as a single region. This choice was based on the near-zero mean GDP elasticity for Europe (countries), which can be traced to the presence of a large positive average long-run GDP elasticity estimate for this region in the data, as seen from the "maximum" column of Table 2 in Oladosu et al. (2018). In addition, given that simulated upper bounds for the two IEA regions are positive (these are the Other IEA and Non-IEA regions with limited data in the meta-regression), the lower and upper bounds for the elasticities used in the simulations are calculated for all regions as the mean value -/+0.009. Table A1-8 shows the final estimates of GDP elasticities used in the BenEStock simulations for this study.

Table A1-8 • Oil price elasticity of the GDP for the IEA stock study

Region	Elasticity		
	Low	Mean	High
IEA North America	-0.0294	-0.0204	-0.0114
IEA Europe	-0.0256	-0.0166	-0.0076
Other IEA	-0.0192	-0.0102	-0.0012
Non-IEA	-0.0209	-0.0119	-0.0029

A1.3 Monte Carlo simulation approach for estimating 30-year benefits

Net benefits and other relevant variables are estimated using Monte Carlo-type simulations. On each iteration, probabilistic disruption sizes and durations (3 to 18 months) are sampled for the four at-risk supply regions, for every year over the 30-year horizon. Market outcomes for each year along this sample time path are calculated based on the random events and stockpile responses. Output values, including benefits, are collected. A simulation comprises thousands (typically 10 000) of such iterations. This allows the determination of expected values and confidence intervals around those average outcomes. The probabilistic outcomes or input values can be stored and used for additional simulations, allowing for more controlled comparisons across sensitivity cases.

Annex 2: Full list of updated parameters and assumptions for the study

Table A2-1 shows a full list of the parameters and assumptions used for the benefit estimates based on extensive discussions with IEA staff and delegates of the SEQ.

Table A2-1 • List of updated parameters for the benefits estimation

Parameter	Value applied in the 2018 study		
General			
Time horizon	2018-47 (30 years)		
Real discount rate	3% (7% alternative)		
Simulated market conditions			
Crude oil price	IEA *WEO 2017* New Polices Scenario		
Oil market projection (reference oil prices, regional demands and supplies, GDPs)	IEA *WEO 2017* New Polices Scenario		
Global supply disruption probabilities – regional probabilities by % loss (and year if time varying), and by duration	Disruption probabilities from new EMF-led 2015 assessment. Events simulated using Monte Carlo simulation		
US GDP elasticity with respect to oil price	Derived from analysis of recent literature. Mean of ~-2.04% with a range of uncertainty (+/- 1%).		
Non-US GDP elasticity	GDP elasticity derived from the available recent literature. ORNL is working to produce updated estimates based on an expanded dataset and quantitative meta-analysis used for estimating oil price elasticities of GDP for the US. 2012 study assumptions provide default values.		
Demand elasticity	Short- and long-run undisrupted demand elasticities from ORNL 2017 meta-analysis/lit review. Variation with disruption size based on approach used by US EIA.		
World net demand elasticities (year 2025)	Oil shortfall	0 mb/d	10 mb/d
	Elasticity after 1 month	-0.06	-0.11
	Elasticity after 12 months	-0.07	-0.15
	Average elasticity over 12 months	-0.07	-0.13
Drawdown threshold	2.0 mb/d net loss of global supply		
Effective OPEC excess capacity (by region and year), and availability	Randomly distributed based upon EMF 2015; 1.1 mb/d expected value, mostly in Saudi Arabia. Spare capacity is assumed to be phased in over 90 days after a disruption. It is unavailable for the first month. After the first month, one-third of the spare capacity becomes incrementally available each month, with full deployment in the fourth month after a disruption. Like the IEA 2012 study, region's spare capacity is assumed unavailable if that region is disrupted.		
Emergency reserves			
US SPR size	695 mb in 2017, 415 mb by 2028.		
US max drawdown/distribution capability	4.4 mb/d. In 2018 the US SPR would be able to maintain 4.4. mb/d for a little less than 90 days. In 2028, when the US SPR is projected to hold 415 mb, the reserve can be drawn down at 4.4 mb/d for less than 60 days.		
Non-US IEA public emergency stock sizes	~800 mb public IEA stock (2018-47 average). IEA Europe public stock levels subject to IEA and EU commitments and change over time.		

Parameter	Value applied in the 2018 study
Maximum non-US IEA public emergency stock effective max draw rate	~8 mb/d
Non-US IEA obligated industry emergency stock sizes	~850 mb industry IEA stock (2018-47 average). IEA Europe industry stock levels subject to IEA and EU commitments and change over time.
IEA obligated industry emergency stock effective max draw rate	All available stock assumed capable to be to be fully drawn down in two months
Non-IEA net importing countries emergency stock sizes	658 mb by 2022. China: 500 mb by 2020. India: 113 mb by 2020. Indonesia: 45 mb by 2021. In the base case, non-IEA stocks are not drawn down in the event of a world oil price shock (0% availability).
IEA and non-IEA drawdown strategies	Co-ordinated draw. The assumed strategy is maximum draw (up to the disruption size) for the first three months, with a sustainable draw thereafter for the remainder of the disruption. The strategy is also constrained by actual maximum drawdown capability for each category of emergency stock, which can depend on the remaining stock in the reserve.
IEA drawdown co-ordination	~45% share for US and 55% for non-US IEA based upon relative size of oil consumption. If either the United States or other IEA regions cannot fulfil its obligation, the other region does increase its draw rate to make up the difference.*

* A prolonged or very large disruption that exhausts the stocks for some member countries earlier than for others has not been experienced in history, so it is not sure what form of drawdown co-ordination would be applied by the IEA Governing Board if a country could no longer meet its drawdown share. For smaller and shorter disruptions, no stockholding country would fall short of its share. For long disruptions, if other countries did not make up the difference, non-compensation could bring forward the time that the IEA cannot compensate for the total loss (but that would leave more stocks for later in the disruption) with limited net effect on benefits. If in a large disruption, with a short or mid-length duration, a shortfall of one country is not compensated for by a larger stock draw of other countries, this could lead to less total stocks used to offset the event, and therefore a loss of benefits. Initial calculations show that in such cases expected stock benefits are reduced by 8%.

Annex 3: Average annual benefits over 30 years

Table A3-1 • Average annual benefits over 30 years (USD/bbl per year, USD 2016)

Case	Low*	Average	High*
Base case	10.96	61.27	119.47
Discount rate (7%)	6.07	36.14	75.11
Lower GDP response (~50% smaller elasticity than base)	7.97	45.22	88.19
Higher GDP response (~50% of larger elasticity than base)	13.85	76.98	149.44
Less elastic net demand (25% smaller elasticity than base)	13.96	75.60	146.46
More elastic net demand (25% larger elasticity than base)	9.02	51.56	100.76
Saudi Arabia slack capacity less available (50% vs. 100% base)	12.97	65.51	124.44
Saudi Arabia slack capacity more available (150% vs. 100% base)	9.40	57.62	114.30
Drawdown threshold, mb/d (1 vs. 2 base)	19.00	70.98	129.27
Drawdown threshold, mb/d (3 vs. 2 base)	0.00	48.29	104.31
Non-IEA stock availability (50% vs. 0% base)	10.96	64.86	128.98
Non-IEA stock availability (100% vs. 0% base)	10.96	67.22	135.02
*Low to high range encompasses 90% of the sample distribution.			

Annex 4: Comparison of 2012 and 2018 study assumptions and results

Table A4-1 shows a full list of the parameters and assumptions used for the benefit estimates based on extensive discussions with IEA staff and SEQ delegates. Values used for this updated study are shown in the third column, and values used for the 2012 study are provided in the second column for comparison.

Table A4-1 • Full list of the parameters and assumptions for the benefit estimates

<table>
<tr><th>Parameter</th><th colspan="3">Value applied in the 2012 study</th><th colspan="3">Value applied in the 2018 study</th></tr>
<tr><td colspan="7">General</td></tr>
<tr><td>Time horizon</td><td colspan="3">2013-42 (30 years)</td><td colspan="3">2018-47 (30 years)</td></tr>
<tr><td>Real discount rate</td><td colspan="3">3% (0% alternative)</td><td colspan="3">3% (7% alternative)</td></tr>
<tr><td colspan="7">Simulated market conditions</td></tr>
<tr><td>Crude oil price</td><td colspan="3">IEA WEO 2011 New Policies Scenario</td><td colspan="3">IEA WEO 2017 New Policies Scenario</td></tr>
<tr><td>Oil market projection (reference oil prices, regional demands and supplies, GDPs)</td><td colspan="3">IEA WEO 2011 New Policies Scenario</td><td colspan="3">IEA WEO 2017 New Policies Scenario</td></tr>
<tr><td>Global supply disruption probabilities – regional probabilities by % loss (and year if time varying), and by duration</td><td colspan="3">Disruption probabilities from EMF 2005. Events simulated using Monte Carlo simulation.</td><td colspan="3">Disruption probabilities from new EMF-led 2015 assessment. Events simulated using Monte Carlo simulation.</td></tr>
<tr><td>US GDP elasticity with respect to oil price</td><td colspan="3">Derived from the literature. Base case = -2.38%, US low/high GDP elasticity = -0.86%/-3.16%.</td><td colspan="3">Derived from analysis of recent literature. Mean of ~-2.04% with a range of uncertainty (+/-1%).</td></tr>
<tr><td>Non-US GDP elasticity</td><td colspan="3">GDP elasticity derived from the available recent literature. Regression analysis was used for extending estimates to countries/regions for which the literature offered no data. IEA Europe = -1.055%, IEA non-Europe, non-US = -1.289%, non-IEA net importing countries = -2.304%.</td><td colspan="3">GDP elasticity derived from the available recent literature. ORNL is working to produce updated estimates based on an expanded dataset and quantitative meta-analysis used for estimating oil price elasticities of GDP for the US. 2012 study assumptions provide default values.</td></tr>
<tr><td>Demand elasticity</td><td colspan="3">Values derived from work by US DoE's EIA. Variation with disruption size based on approach used by US EIA. See below.</td><td colspan="3">Short- and long-run undisrupted demand elasticities from ORNL 2017 meta-analysis/lit-review. Variation with disruption size based on approach used by US EIA.</td></tr>
<tr><td rowspan="4">World net demand elasticities (year 2025)</td><td>Oil shortfall</td><td>0 mb/d</td><td>10 mb/d</td><td>Oil shortfall</td><td>0 mb/d</td><td>10 mb/d</td></tr>
<tr><td>Elasticity after 1 month</td><td>-0.08</td><td>-0.13</td><td>Elasticity after 1 month</td><td>-0.06</td><td>-0.11</td></tr>
<tr><td>Elasticity after 12 months</td><td>-0.11</td><td>-0.19</td><td>Elasticity after 12 months</td><td>-0.07</td><td>-0.15</td></tr>
<tr><td>Average elasticity over 12 months</td><td>-0.10</td><td>-0.16</td><td>Average elasticity over 12 months</td><td>-0.07</td><td>-0.13</td></tr>
<tr><td>Drawdown threshold</td><td colspan="3">2.0 mb/d net loss of global supply</td><td colspan="3">2.0 mb/d net loss of global supply</td></tr>
</table>

Parameter	Value applied in the 2012 study	Value applied in the 2018 study
Effective OPEC excess capacity (by region and year), and availability	Saudi Arabia assumed to have 2 mb/d of excess capacity of which a maximum of 50% would be used in the event of a disruption. All other members of OPEC are assumed to have a combined 0.832 mb/d, 100% of which would be made available in the event of a disruption. A region's spare capacity is assumed unavailable if that region is disrupted.	Randomly distributed based upon EMF 2015; 1.1 mb/d expected value. Spare capacity is assumed to be phased in over 90 days after a disruption. It is unavailable for the first month. After the first month, one-third of the spare capacity becomes incrementally available each month, with full deployment in the fourth month after a disruption. Like the IEA 2012 study, region's spare capacity is assumed unavailable if that region is disrupted.
Emergency reserves		
US SPR size	697 mb	695 mb in 2017, 415 mb by 2028.
US max drawdown/ distribution capability	4.4 mb/d for 90 days	4.4 mb/d initially. In 2018 the US SPR would be able to maintain 4.4. mb/d for a little less than 90 days. In 2028, when the US SPR is projected to hold 415 mb, the reserve can be drawn down at 4.4 mb/d for less than 60 days.
Non-US IEA public emergency stock sizes	~850 mb public IEA stock (2013-42 average). IEA Europe public stock levels subject to IEA and EU commitments and change over time.	~800 mb public IEA stock (2018-47 average). IEA Europe public stock levels subject to IEA and EU commitments and change over time.
Maximum non-US IEA public emergency stock effective max draw rate	~8 mb/d	~8 mb/d
Non-US IEA obligated industry emergency stock sizes	~800 mb industry IEA stock (2013-42 average). IEA Europe industry stock levels subject to IEA and EU commitments and change over time.	~850 mb industry IEA stock (2018-47 average). IEA Europe industry stock levels subject to IEA and EU commitments and change over time.
IEA obligated industry emergency stock effective max draw rate	All available stock assumed capable to be to be fully drawn down in two months	All available stock assumed capable to be to be fully drawn down in two months
Non-IEA net importing countries emergency stock sizes	610 mb public non-IEA stock (2013-42 average). In the base case non-IEA stocks are not drawn down in the event of a world oil price shock (0% availability).	658 mb by 2022. China: 500 mb by 2020. India: 113 mb by 2020. Indonesia: 45 mb by 2021. In the base case non-IEA stocks are not drawn down in the event of a world oil price shock (0% availability).
IEA and non-IEA drawdown strategies	Co-ordinated draw. The assumed strategy is maximum draw (up to the disruption size) for the first three months, with a sustainable draw thereafter for the remainder of the disruption. The strategy is also constrained by actual maximum drawdown capability for each category of emergency stock, which can depend on the remaining stock in the reserve.	same
IEA drawdown co-ordination	~45-55% share for US and non-US IEA based upon relative size of oil consumption. If either the United States or other IEA regions cannot fulfil its obligation, the other region does increase its draw rate to make up the difference.	same

Table A4-2 shows a full list of the parameters and assumptions used for the cost estimates based on extensive discussions with IEA staff and SEQ delegates.

Table A4-2 • Full list of parameters for the cost estimation

Parameters	Value 2012	Value 2018
Project life of terminal	30 years	30 years
Amortisation period	30 years	30 years
Residual value	EUR 0	EUR 0
Inflation	3% per year	2% per year
Discount rates (base case/sensitivity case)*	3% and 7%	3% and 7%
Rate of exchange (USD/EUR)	1.3	1.174
Tank farm size	100 000-500 000 m³	100 000-500 000 m³
Investment in tanks/m³ (excl. steel)	EUR 93/m³	EUR 93/m³ excl. steel (cost incl. steel EUR 127/m²)
Steel price	EUR 1 200/Mt	EUR 1 450/Mt-EUR 1 650/Mt
Investment in jetties	EUR 30 million/jetty	EUR 30 million/jetty
Land-side loading/unloading	EUR 0	EUR 0
Land utilisation ratio	3.5 m³/m²	3,5 m³/m²
Land lease expenses	EUR 5/m² per year	EUR 7.40/m² per year
Operating expenses	EUR 10/m³ per year	EUR 10/m³-EUR 12.50/m³ per year
Corporate tax	25%	24%
Refreshment interval	6 years	6 years
Duration of refreshment exercise	3 months	3 months
Ageing fee/shipping fee*	USD 4/Mt	USD 4/Mt (and USD 15/Mt for remote storage location)
Cost of alternative storage during refreshment/ ticket cost	EUR 24/m³ per year	EUR 18-22.50/m³ per year
Terminal handling cost	EUR 1/Mt	EUR 1/Mt
Product share in relation to total obligation	30%	30%
Crude price	USD 125/bbl	USD 59.37/bbl
Product price	USD 1 025/Mt	USD 577/Mt
Average product density	0.8 kilogrammes per litre	0.8 kilogrammes per litre
Range of commercial storage rates (above-ground tanks)	EUR 18/m³-EUR 24/m³ per year	EUR 20/m³-EUR 24/m³ per year
Range of commercial storage rates (caverns)	EUR 4/m³-EUR 10/m³ per year	EUR 7/m³-EUR 12/m³ per year

* The appropriate value of the discount rate depends on many factors, including source of funds, affected stakeholders and level of risk. For public assets, such as emergency stocks, the discount rate is often assumed to be the risk-free interest rate on government funds. For the 2018 update, both cost and benefit estimates are based on real discount rates.

** For remote storage location, the ageing and shipping fees are higher and a value of approximately USD 15/Mt should be taken into account; trading margin is included in this cost. The change in cost from USD 4/Mt to USD 15/Mt has a small effect on the total costs: (((15-4)*0.8)*(1.03)^6)/6 = USD 1.75/m³ per year. For a stock composition of 70% crude oil and 30% products, and in barrel per year, it is approximately USD 0.10/bbl per year.

Comparison of current results to 2012 study benefits results

In the current study, annual net benefits are about 10% higher on a USD/bbl per year basis. One factor is that there are fewer barrels of IEA emergency stocks in the projected future, given planned sales by the US SPR, and reductions in consumption or import levels in some IEA countries. There are other factors at work, however, in offsetting directions. These are summarised in the annex below. As a result, absolute stockholding total benefits in billions of USD 2016 are within 0.5% for the two studies.

Table A4-3 • Stockholding benefits, base case, for current 2018 study and 2012 study (low to high range encompasses 90% of the sample distribution)

	Low (5%)	Average	High (95%)
IEA 2018 study base case (USD 2016)	10.96	61.27	119.47
IEA 2012 study base (USD 2010)	8.88	50.68	97.27
IEA 2012 study base (USD 2016)	9.78	55.79	107.10

Annex 5: Summary of factors that caused estimates to change from 2012 study to 2018 study

Factors that increased benefits since 2012 study:

- In 2014, the IMF revised GDP measured in purchasing power parity upwards for most countries. Those changes increased model benefits by 7%.
- Real GDP forecasts in later study time horizon (2018-47 versus 2013-42) increased the size of GDP at risk.
- Assumed lower demand flexibility in response to price changes resulted in higher price effects from shocks compared with previous study.
- Spare capacity is slightly lower and phased in over time. Revision based upon adopting EMF 2015 approach and discussions with Aramco.
- US emergency stocks are less, resulting in higher USD/bbl of emergency stocks (though lower benefits in billion USD).

Factors that decreased benefits since 2012 study:

- Forecast reference real oil prices are 35% lower in current study than previously. This results in lower avoided net import costs.
- Lower net imports for total IEA (and US is expected to be a net exporter by ~2030).
- Using EMF 2015 disruption probabilities results in less significant price shocks than assumed in previous study, which used EMF 2005 probabilities.
- GDP sensitivity to price shocks has been revised down in most of the benefit regions.

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Acronyms, abbreviations and units of measure

Acronyms and abbreviations

ARDL	autoregressive distributed lag
BFOE	Brent, Forties, Oseberg and Ekofisk
CAPEX	Capital expenditure
CFR	Council on Foreign Relations
CTMD	constrained technical maximum draw
DoE	Department of Energy
ECB	European Central Bank
EIA	Energy Information Administration
EMF	Energy Modeling Forum
EUR	euro
GDP	gross domestic product
HSSE	health, safety, security and environment
ICE	Intercontinental Exchange
IEA	International Energy Agency
IMF	International Monetary Fund
NATO	North Atlantic Treaty Organization
NPV	net present value
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OPEX	operating expense
ORNL	Oak Ridge National Laboratory
RGDP	regional GDP
SEQ	Standing Group on Emergency Questions
SPR	Strategic Petroleum Reserve
US	United States
USD	United States dollar
WEO	*World Energy Outlook*
WTI	West Texas Intermediate

Units of measure

bbl	barrel
m^2	square metre
m^3	cubic metres
mb/d	million barrels of oil per day
Mt	million tonnes
USD/bbl	US dollars per barrel

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