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King Abdullah Petroleum Studies and Research Center

Balancing Energy Security Priorities: A Portfolio Optimization Approach to Oil Imports

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About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is a non-profit global institution dedicated to independent research into energy economics, policy, technology and the environment across all types of energy. KAPSARC's mandate is to advance the understanding of energy challenges and opportunities facing the world today and tomorrow, through unbiased, independent, and high-caliber research for the benefit of society. KAPSARC is located in Riyadh, Saudi Arabia.

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Key Points

This study applies financial portfolio theory to the energy security issues of East Asia's major energy importers: China, Japan, South Korea and Taiwan. We calculate the relative risks associated with the dynamics of oil imports, and the import prices paid, and estimate the efficient frontiers for corresponding import portfolios. Last, we run several scenarios which simulate the effects of restructuring oil import portfolios and external disruptions. We find that:

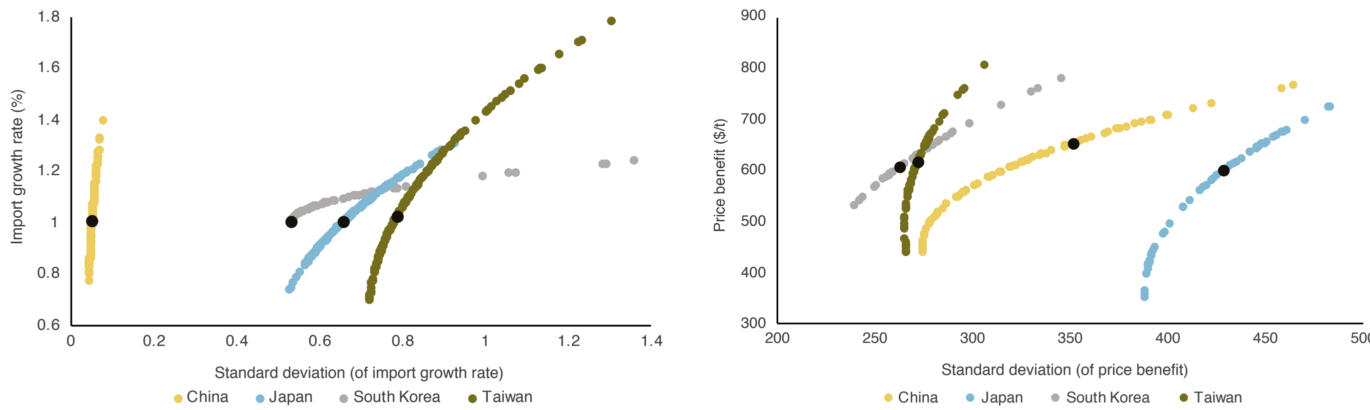
The composition of oil import portfolios determines varying risk levels for given oil import growth rates and average import prices (see Figure 1), pointing to different energy security priorities for the economies studied.

Increasing the share of oil imports originating from Saudi Arabia would improve the portfolio performance of China, but result in higher portfolio volatility for the other importers.

The short-run impact of a fully enforced Iranian oil export embargo would increase portfolio risk across the board within a 3% to 15% range. However, the subsequent substitution of Iranian oil imports by other suppliers would prove beneficial for Japan and Taiwan.

The risk premium associated with passing through the Malacca Straits, 10% of the price of the cargo, would result in a 27.5% increase in price volatility for China's oil imports. The negative impact on its average import price level, however, would be less pronounced – at 2.6% compared with a range of between 5.2% to 5.8% for the other importers.

Figure 1. Efficient oil import frontiers targeting import growth and import price benefits ($1,000/tonne – import price/tonne).



Note: Black dots represent average monthly values observed in 2017.
Source: KAPSARC research.

Summary

The notion of energy security emerged in the 1970s, following a wave of energy crises. It has evolved from the initial paradigm of assuring sufficient energy supplies to include a price affordability perspective and, eventually, a plethora of energy-related issues such as infrastructure, environmental impact, societal effects, energy efficiency and governance. However, based on the energy security definitions adopted by major international organizations and relevant government policies, the security of physical supply and price affordability remain the key pillars of this paradigm.

Recent trends in global energy markets may suggest an ongoing shift in energy security priorities, from physical supply concerns to price/affordability considerations. Higher fungibility of energy sources and individual fuels, increasing the connectivity of regional fuel markets and the rapid deployment of renewables, should reduce the pressure to secure physical supplies of fuels and facilitate increased reliance on market mechanisms. However, these developments could be offset by escalating global financial, economic and geopolitical risks. This challenging dynamic calls for an energy security assessment framework that will capture the trade-offs between the security of supply and affordability, the associated risks and potential vulnerabilities, as well as capturing the idiosyncrasies of individual economies.

Conventional approaches to energy security can shed some light on this topic, but they contain methodological drawbacks. For instance, energy security indices and indicators lack a consistent aggregation methodology, often failing to reflect rapid changes due to the time required to update the underlying data points. These indicators generally do not reflect bilateral relationships and provide no insights into future developments. Microeconomic and operations research methods often depend heavily on the subjective judgments of researchers in providing modeling inputs, and energy systems models often miss short-run impacts — e.g., those caused by price fluctuations — due to aggregated representation and long iteration steps.

This study uses the optimal portfolio theory to evaluate the physical supply and price components of energy security. We assume that oil import portfolios are characterized by a return, represented by the growth rate of oil imports or the average import price, and associated risks, represented by portfolio variance and portfolio composition. Both of these elements are based on historical shipment and price data. We derive efficient portfolio frontiers and construct the oil import growth and oil import price portfolios for the four major Asian oil importers: China, Japan, South Korea and Taiwan. This method captures the trade-offs between high growth/best price terms and the concentration of suppliers, and portfolio diversification to lower the associated risks.

A comparison of the efficient portfolio frontiers for import volumes and average import prices also allows us to identify the energy security priorities of individual economies. Thus, we note that China has managed to assemble a diversified portfolio of oil imports. Not only is the risk associated with its current import growth level a magnitude lower than those of its regional peers, but the shape of China's efficient frontier curve also suggests that further increases in imported oil volumes could be achieved without a significant spike in volatility. South Korea and Taiwan, on the other hand, seem to prioritize economic benefits, selecting their oil import portfolios based on the best possible price terms. Japan's import growth frontier is similar to those of South Korea and Taiwan, but its price benefit curve lags them in the price/risk balance – suggesting that its portfolio structure could be improved.

The differences in the structure of the four countries' oil import portfolios result in significant variations when shifting existing oil supplies. Increasing the share of imports from a particular supplier, even the one considered most reliable and which also offers beneficial price terms, can yield negative effects depending on the portfolio composition, such as an increasingly volatile growth rate of oil imports and average import price. This effect is observed when the share of Taiwan's oil imports from Saudi Arabia is increased by 10%. Such an increase would be beneficial for China from the point of view of both the average price and the associated risk.

The outcomes resulting from potential external disruptions also vary significantly for the importers studied. In the case of a fully enforced Iranian oil embargo, the volatility of an oil import portfolio increases from 3% for Taiwan to 15% for South Korea. However, in the aftermath of the immediate impact of the embargo, replacing Iranian shipments with oil from other suppliers could improve the portfolio performance for both Japan and Taiwan, compared with the continued negative impact observed for China and South Korea.

Finally, we test the resilience of portfolios to the risk premium – set at 10% of the import cost – associated with passing through the Malacca Straits. China would see the smallest price impact, at minus 2.6%, compared with the minus 5.2%-5.8% range observed for the other three economies. However, this scenario would result in a much more significant increase in China's portfolio price volatility, at 27.5%.

The energy security evaluation framework presented in this study has limitations. It deals only with diversifiable risks and does not account for systemic or systematic risks – i.e., those that impact the whole market — and its scope is limited to the short term. Nonetheless, the framework has a number of advantages. It allows for the risk/benefit analysis of the security of supply and affordability and the trade-offs between them. It also takes into consideration individual portfolio characteristics and can be used for scenario and vulnerability analyses. Its application can be extended to the long term, based on appropriate data inputs. It can also help to assess the energy security dilemma from the energy exporter's perspective.

Energy Security: Another Paradigm Shift?

The subject of energy security has been a focus for policymakers, academics and market participants for several decades. Spurred by the energy crises of the 1970s, the concept of "assuring sufficient energy supplies" was introduced by Willrich (1976) and further explored by researchers in the 1970s and 1980s. During this period, fuel importing countries primarily viewed energy security as supply availability. The oil price fluctuations resulting from the 1990-1991 Gulf War led researchers to broaden the concept to include an economic perspective, in particular, the affordability of energy and its impact on national welfare.

Research into energy security has developed considerably since the beginning of the 21st century, characterized by a growing number of studies with a broad scope. This research has also received increased attention from governments and international organizations. Recent studies suggest that the concept of energy security should encompass an extensive list of issues, including infrastructure (Scheepers et al. 2007), environmental impact (Greenleaf et al. 2009), societal effects (Kemmler and Spreng 2007), energy efficiency (Hughes 2009), and governance (Yergin 2006), among others. While the extended definition of energy security now includes energy diversification and interdependent energy security issues, it also risks trying to categorize all energy issues as energy security problems. The perspectives of international energy organizations on energy security and its definition provide a reality check against this concept creep.

The following is a sample of definitions of energy security adopted by key global stakeholders:

> International Energy Agency: "Uninterrupted availability of energy sources at an affordable price" (IEA 2018);

> United Nations: "The continuous availability of energy, in varied forms, in sufficient quantities, and at reasonable prices" (UNDP 2000);

> European Union: "The European Union's long-term strategy for energy supply security must be geared to ensure, for the well-being of its citizens and the proper functioning of the economy, the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development." (European Commission 2000).

Evidently, security of physical supply and price affordability remain the principal components of the energy security paradigm. Governments and other market participants may, within any given time horizon, prioritize either of these two components. In doing so, they will try to balance the corresponding trade-offs, which are dependent on a number of factors including geographic location, resource endowments, economic development and geopolitical considerations, among many others.

Shifts in global energy markets significantly impact energy security and the strategies relevant to it. Recent trends suggest that concerns over the security of physical supply are giving way to economic concerns, as the market plays an increasing role in addressing the security of physical supply.

> Fungibility of energy sources is increasing, both globally and in the key energy consuming regions such as Asia Pacific. The share of electricity in global primary energy consumption has risen from 13.8% in 2000 to 16.3% in 2017, whereas the Asia Pacific region has seen a rise

- from 13.3% to 17.2% over the same timeframe (BP 2018).

- Individual fuels, such as oil, are also becoming more fungible. The Nelson Complexity Index (NCI), which measures the sophistication of oil refineries, rose from 7.9% in 2000 to 9.3% in 2017 globally, and from 7% to 9.7% during the same period in the Asia Pacific region (Eni 2018).

- Regional fuel markets are becoming more interconnected through technological advances and increasing international trade. The volume of liquefied natural gas (LNG) traded globally has almost tripled since the beginning of this century.

- The rapid deployment of renewables is reducing the share of traditional fuels in the energy mix.

These positive developments are still, to an extent, offset by geopolitical risks including trade wars and sanctions that impact key energy producers (e.g., Russia and Iran) and consumers (e.g., the United States [U.S.] and China), as well as the rise of protectionist policies and escalating tensions between major world powers. These risks may lead to supply disruptions and to more expensive energy.

Energy security indicators are sending mixed messages as to whether securing physical energy supplies has become less of a concern for countries than it used to be. Outward foreign direct investment (ODI) in energy by fuel import-dependent economies such as China and South Korea has been declining both in absolute and in relative (compared with total ODI) terms (see Figure A1 in Appendix 1 for details). However, these economies are aggressively building strategic petroleum reserve (SPR) capacities, e.g., an estimated 500 million barrels in China and 146 million barrels in South Korea (Oil Price 2017). The trends in the market concentration of the international fuel trade, measured by the Herfindahl-Hirschman Index (HHI), vary by fuel type and importer. A general increase in HHI for coal (see Figure A2, Appendix 1) implies that economies are less focused on diversification and may reflect their declining concerns about supply security. The HHI of oil imports has been relatively steady over the last decade, with the notable exception being the vastly diversified Chinese import portfolio, while global natural gas imports have become much more diversified due to increased LNG trade.

A review of the current energy security policies of the world's major energy importers shows that their main priority continues to be security of supply. China's intensive development of its SPRs should mean that it can cover 90 days of oil demand from storage facilities by 2020. The country's Five Year Plan for the Development of Foreign Trade sets out the goals of "sustained and steady growth of energy resources and commodity trade, and [to] ensure the supply of domestic markets" and "supporting powerful companies" to "go global, develop overseas resources, energy, and processing and production" (MOFCOM 2017). South Korea's Energy Master Plan also emphasizes diversifying existing energy routes and expanding its domestic stockpiling capacity (MOTIE 2014).

Recent shifts in global energy markets and rapidly changing international economic and geopolitical conditions call for tools to assess energy security in terms of supply security, economic benefits and the trade-offs between them. Such tools would assist market participants in developing strategies and understanding vulnerabilities under existing and future economic and political scenarios. They would also help analysts and academics in their examination of particular economies and market participants. The following section reviews the existing approaches to assessing energy security and their applicability in the current environment.

Conventional Approaches to Energy Security Analysis

Measuring energy security can be challenging, given its complex multidimensional structure and loosely defined scope. Hence, there is no single agreed indicator which would capture the entire concept. On the contrary, the recent proliferation of research on the subject of energy security has resulted in a plethora of proposed assessment methods. Scholars in the fields of economics, political science, the environment, energy technology and other domains view energy security differently and, consequently, propose different methodologies. This enriches energy security research but at the same time causes analyses of the subject to lack an integrative theoretical foundation and consistent criteria.

This problem is clear in the area of energy security indices and indicators. The tendency to stretch the definition of energy security has led to a multitude of indicators intended to capture all possible applicable metrics. For instance, Sovacool (2011) proposes 200 indicators, grouped into 20 categories, to analyze energy security in the Asia Pacific region. Using only the classical definition of energy security as “adequate energy supply at an affordable price” would – to a certain extent – limit the number of indicators that could be considered relevant. However, any given subcategory related to securing physical supplies, or energy economics, can be further disaggregated into a plethora of indicators. Thus, the seemingly straightforward concept of import dependency may include a multitude of criteria. They include the current and historical ratios of imports, consumption and domestic production for specific fuels and regions (expressed in volumes and values), diversification indices and the shares of particular suppliers, coefficients reflecting the impact of energy imports on total imports and the balance of payments, and the energy imports to gross domestic product (GDP) ratio, among others.

Besides the significant resources required to track such a large number of indicators, indices and coefficients, there is the additional challenge of deciding on the relative importance of these indicators and how to present this information to decision-makers in a comprehensible format. The seemingly obvious solution would be to aggregate indicators into indices that reflect a particular aspect of energy security. This approach is used in the Index of U.S. Energy Security Risk compiled by the Global Energy Institute (2017). Specific metrics are aggregated into categories, which are then aggregated into sub-indices that, in turn, make up the index. However, this methodology also has its drawbacks. First, the weightings of individual indicators in sub-indices are by default arbitrary. Second, this method omits qualitative indicators that can have a substantial impact on energy security, e.g., relations with key suppliers, stability in major exporting and transit regions, or non-tariff trade barriers.

The aggregation issue aside, the energy security indicators require certain caveats. Their static nature, conditioned by the update time of underlying data points, often fails to reflect rapid changes in the energy markets, the global economy and international relations. The indicators do not generally represent bilateral relationships between suppliers and consumers and, without appropriate modeling tools attached, they provide no insights into future developments.

The methods and approaches of microeconomics and operations research, such as supply chain analysis, can be used to analyze risk and model simulations in the field of energy security. These frameworks allow for risk minimization assessments when optimizing energy imports, given that the risks are known and quantifiable. Zhang et al. (2017) developed a model to optimize China's LNG imports, based on the importing costs, the exporting country and the shipping route risks. They used the model to simulate the effects of changes in input factors and extreme events. However, it should be noted that the results of such simulations depend heavily on the subjective judgment of those providing the modeling inputs.

More comprehensive models, usually derived from energy system models, e.g., Rioux et al. (2019), (EIA 2017), can provide a broader perspective on energy import security and its interactions with domestic energy systems and global fuel markets. This approach, however, is quite resource-intensive and less suited to analyzing short-run impacts, such as those caused by price fluctuations, due to an aggregated representation and long iteration steps. Finally, political science provides another perspective on energy security (Garrison 2010, Hughes and Lipscy 2013), introducing the elements of the bargaining process, distribution of power and interdependence between actors.

The overview of traditional methodologies applied in the energy security sector shows that none of these approaches on its own represents a clear evaluation mechanism for the trade-off between the economic/price and physical supply security components and the associated risks, which is at the core of the classic energy security definition, as discussed in the previous section. The next section of this paper describes our proposed method, developed based on the financial analysis toolkit, of addressing this issue.

Portfolio Optimization of Energy Imports

Theoretical background

The concept of minimizing portfolio risk, represented by variance, for any given level of expected return or, conversely, maximizing the expected return for a given level of risk, was first introduced by Markowitz (1952). Since then, this theory has been extensively applied both within and outside the financial portfolio domain.

The energy crises and the increased price volatility of internationally traded fuels in the 1970s prompted the use of portfolio theory in the field of energy. Bar-Lev and Katz (1976) used portfolio theory to explore the efficiency of fossil fuels procurement by U.S. utilities. Since then, portfolio theory has been used to assess energy projects and investment decisions (Westner and Madlener 2010), maximize yields in power generation subsectors (Medimorec and Tomsic 2015), optimize the power generation industry as a whole (Awerbuch and Berger 2003), and rationalize national energy consumption mixes (Humphreys and McClain 1998).

In the efficient portfolio framework, the risk component is consistently represented by the portfolio variance or standard deviation. This allows for the optimization, i.e., the minimization or maximization, of a broad range of parameters that can be applied to the energy sector. These may include generation or fuel input costs, earnings represented by the project's net present value and internal rate of return, the spread between power tariffs and generation costs, as well as non-financial criteria such as the capacity factor. Optimization models can also be subject to external constraints, including available capital, infrastructure capacity, the minimum required share of a particular technology, or environmental externalities.

The efficient portfolio framework is mostly used for domestic energy system-related issues. However, it also covers elements of energy security, including security of energy supply and the impact of price/cost fluctuations. Studies that apply the portfolio approach to energy and fuel imports primarily focus on portfolio risk analysis for existing and historical import levels. They generally define risk based on a variance in import costs (Wu et al. 2007) or the supplier's economic and political environment (Ge and Fan 2013; Wabiri and Amusa 2010). The latter is used as a proxy for both physical supply and price

Assumptions and limitations of the efficient portfolio theory

The theoretical model of the efficient portfolio determination relies on a set of assumptions and fundamentals such as the normal distribution of asset returns, the rationality of agents with risk averse preferences, price taking behavior, and the absence of borrowing constraints. We consider that an economy's oil importing strategy can be plausibly assumed to satisfy the last three characteristics. Irrational and speculative behavior is primarily associated with individual investors in the financial markets, not with importers reliant on physical supplies of energy to run the economy. It is also a reasonable assumption that buyers will be price takers in the international oil market. The results of Jarque-Bera tests — a joint Lagrange multiplier test of the residuals' skewness and kurtosis — for the sampled set of economies and their variables suggest no serious indication of non-normality of the return.

security risks. This approach is prone to the same drawbacks inherent in energy security coefficients, as discussed in the previous chapter. Moreover, to our knowledge, no studies have yet derived an energy import efficiency frontier where importers could assess the trade-offs between cheaper or more abundant supply sources and associated risks.

This study attempts to address these gaps in existing research by using the optimal portfolio theory approach to evaluate both physical supply and price security components for energy imports in order to derive corresponding efficient import portfolio frontiers.

Scope of the study

The purpose of this study is to analyze the growth-instability and price-instability relationships in the structure of the crude oil imports of the four major East Asian economies: China, Japan, South Korea and Taiwan. This analysis provides a novel perspective on the energy security issue and can be used by energy importers to assess their current energy security status and potential vulnerabilities. It can also help importers to analyze scenarios and develop relevant strategies.

An economy's total oil import volumes are composed of import flows from various suppliers, with specific growth rates and price terms associated with each particular supplier. In this sense, as with the original Markowitz (1952) model, total imports may be considered as a portfolio, where the overall oil import growth rate is equal to the weighted sum of the growth rates of import suppliers, and which is, therefore, subject to a diversification effect. This paper considers the oil import portfolio of an economy. This is characterized by the return, uncertainty and the portfolio structure (the oil suppliers for a particular importing economy). The return is represented by either growth in imported volumes or lower import prices and uncertainty is expressed as the variability in imports or the price terms of a particular supplier.

In the first phase, we construct two efficient portfolio frontiers for each economy to assess the following:

> The oil import growth portfolio: Where the return variable is represented by the monthly growth rate in oil import volumes and variance is derived from the structural composition of the portfolio, based on the historical data of imported volumes from individual suppliers. This portfolio represents the trade-off between high growth and concentration and lower risk through diversification.

> The oil import price portfolio: In this portfolio, the return variable reflects the average monthly oil price paid by an importer. To adhere to the return maximization framework, we introduce a return variable called the 'price benefit measure,' calculated as $1,000 per tonne ($/t) of imported oil minus the actual import price ($/t) paid at the border. The portfolio variance is estimated based on fluctuations of the price benefit associated with individual suppliers and their share of a particular economy's total oil imports. This portfolio represents the trade-off between concentrating on a few suppliers that offer the best price terms and reducing the economy's price risks through diversification.

These portfolios cover two major aspects of energy security concerning fuel imports: securing physical supply, and obtaining favorable price terms while minimizing the associated risks. The comparison of an economy's efficient frontier curves, derived using these two models, also allows for an analysis of the trade-offs between the physical and economic dimensions of fuel import energy security.

We develop several scenarios in the second phase of the analysis to assess the potential impacts on the importers' portfolios from changes in portfolio structure, geopolitical events and the re-evaluation of risk premia associated with particular supply routes.

It should be noted that the model's output reflects relatively short-term effects, as the portfolios are calibrated using monthly import data. The risk assessment in this study is also limited to specific risks, i.e., the risks surrounding a particular supplier/import route that can be diversified. It does not include systemic risks that can destabilize an entire industry or market, or systematic risks that can affect the overall market.

Appendix 2 contains a detailed description of the model and data sources used in this study.

Scenario design

We develop several scenarios to assess how oil import portfolios and their major components, i.e., import volume growth rates, price benefits and corresponding volatilities, are impacted by potential disruptions and portfolio restructuring.

We establish a baseline scenario to place the oil importing economies on their respective efficient frontier curves using 2017 average monthly oil import data. We then estimate the consequences of portfolio restructuring by increasing the share of oil imports from Saudi Arabia. In the next phase, we assess the potential immediate and later impacts of Iranian sanctions on the volatility of oil import portfolios. Finally, we evaluate how the risk premium associated with passing through the Malacca Straits affects the price levels and price volatility of oil import portfolios. Table 1 summarizes the scenarios applied in this study.

Table 1. Energy security scenarios used in this study for oil importers.

Scenario	Description
Baseline 2017	For the four big East Asian oil importing economies, China, Japan, South Korea and Taiwan, we estimate the points on the efficient frontier curves that most closely correspond to the recently observed average monthly growth rates of oil import volumes and oil import price benefits for each economy.
Increased Saudi imports	We increase the share of oil imports from Saudi Arabia by 10% for each of the four economies. Imports from other suppliers are reduced proportionally, so that total import volumes remain the same.
Iranian embargo	We simulate the short-run impact of an effective Iranian oil export embargo. Importing economies end all oil imports from Iran and these volumes are not substituted by other suppliers.
Iranian replacement	Existing suppliers proportionally substitute oil imports from Iran.
Malacca Straits risk premium	We add a 10% risk premium to the cost of oil imports that pass through the Malacca Straits.

Source: KAPSARC.

Results and Discussion

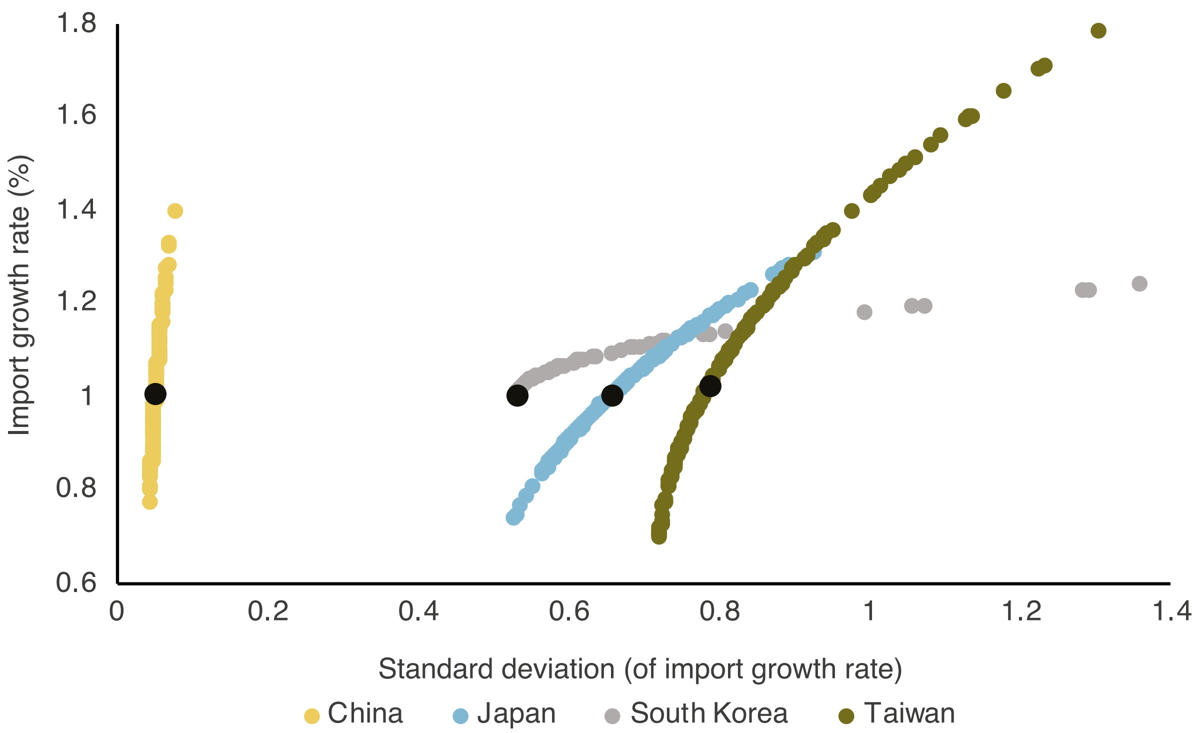
Establishing efficient frontiers of energy imports

Figure 1(a) shows efficient portfolio frontiers for imported oil volumes derived for China, Japan, South Korea and Taiwan. The chart reflects a trade-off between the monthly growth rate of imports (vertical axis) and associated risks, represented by its standard deviation (horizontal axis). Average monthly growth rates over the last 12 months, which are used as the basis for our Baseline 2017 scenario, are marked by black dots. For China, Japan and South Korea these values lie within a narrow range of 1.0122, 1.0117 and 1.0026, respectively. Taiwan stands out against its peers, with a 1.0437, or 4.37%, average monthly growth.

Note that monthly fluctuations in imported oil volumes do not necessarily represent economies' long-term consumption and import patterns. For instance, Taiwanese oil imports were stagnant in 2017 and have grown only 15% since 2001. However, month-on-month fluctuations can reach up to 30%. These dynamics can be driven by seasonality, oil storage management and refinery operations, especially in the smaller economies, and a reliance on the spot market.

Economies with similar average monthly import growth rates have varying risk levels due to the differences in the composition of oil import portfolios. The corresponding standard deviations of imported oil volumes estimated for the Baseline 2017 scenario are 0.055 for China, 0.67 for Japan, 0.53 for South Korea and 0.798 for Taiwan.

Figure 1(a): Efficient oil import frontiers: import growth rate, 2017.



Note: Black dots represent average monthly values observed in 2017.
Source: KAPSARC research.

China has the lowest risk import portfolio among the four oil importers covered in this study. The standard deviation of its portfolio in 2017 is much smaller than those of its peers. Its steep frontier curve also implies that China can substantially increase its monthly oil imports without major negative implications for its overall portfolio risk.

The shape and position of China's efficient frontier curve mirror the economy's considerable efforts to ensure security of supply. These efforts are unsurprising given China's current significant level of oil import dependence, at about 70% of domestic consumption (CEIC 2018), and strong demand projections for the coming decade – a 2.1% compound annual growth rate (CAGR) until 2030, according to the Institute of Energy Economics, Japan 2019 Outlook (IEEJ 2018). It can be debated, however, whether the costs associated with securing and diversifying oil imports can be optimized and whether the current portfolio risk is already below the level which can be regarded as sufficiently tolerable.

The other importers analyzed in this study have even higher oil import dependence rates than China, as they have to rely entirely on external supply sources. Nonetheless, their oil imports are less diversified and more volatile. Far behind China's benchmark, South Korea has the lowest portfolio risk among the remaining three importers under the Baseline 2017 scenario. However, the shape of its frontier curve suggests that it would not be able to easily accommodate a sharp increase in monthly imported volumes, which could occur as a result of supply disruptions or other unforeseen events. In this case, its oil imports portfolio risk would increase exponentially and, starting from certain import growth levels, South Korea's portfolio could become the riskiest among the four importers covered in this study.

An efficient frontier curve of such a shape may represent a concern, given South Korea's recent steady growth in oil imports of around 3%-4% per annum and a projected, albeit moderate (0.2% CAGR), forecasted increase in oil demand until 2030 (IEEJ 2018). This may also signal a lack of focus on oil imports in the country's national energy policy and energy security agenda.

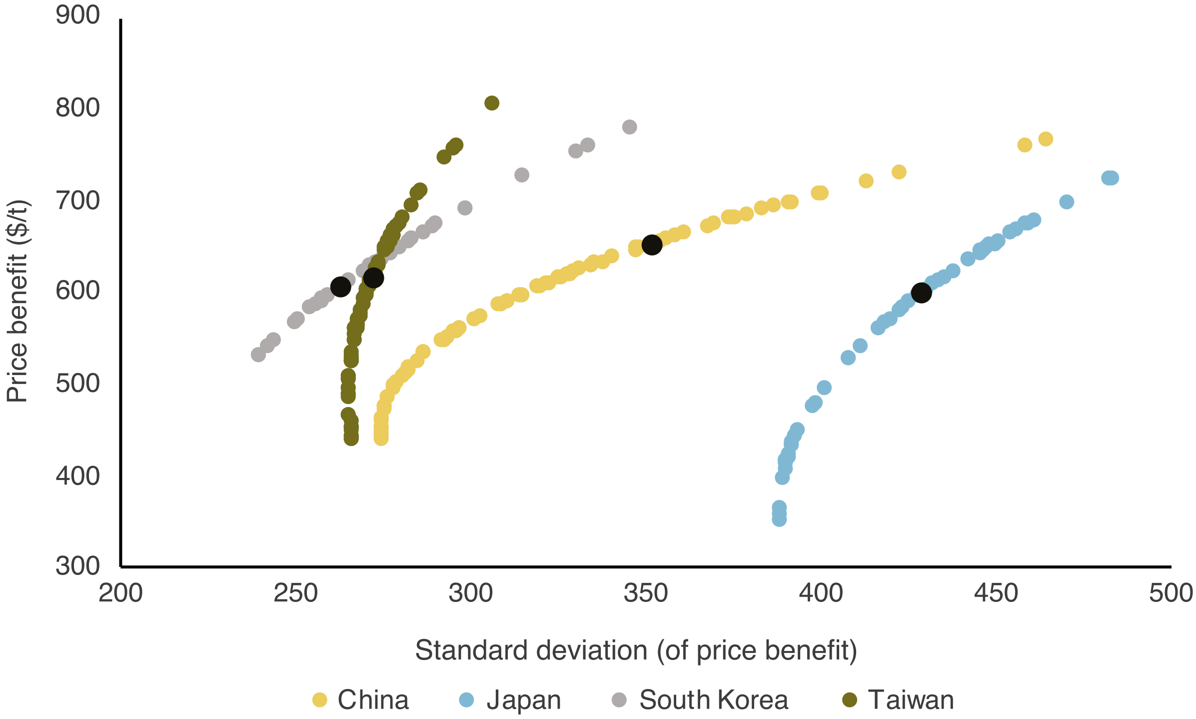
Japan and Taiwan demonstrate efficient frontier curves of a similar shape. Both economies have lacked substantial oil import growth in recent years – imports have decreased in Japan and plateaued in Taiwan – and both are expected to see a drop in consumption over the coming decade. As of 2017, Japan was somewhat better positioned in terms of its oil import growth portfolio risk, due to relatively higher supplier diversification. Conversely, Saudi Arabia and Kuwait together supplied more than 50% of Taiwan's oil imports in 2017 (World Bank 2018).

Figure 1(b) shows a comparison of the price/risk component of oil import security for the four East Asian importers covered in this study. The vertical axis represents the price benefit measure – the difference between $1,000/tonne(t) and the actual price of an imported tonne of oil paid for at the border – calculated on a monthly average basis. The horizontal axis represents the associated price volatility, expressed as a standard deviation.

The price benefits estimated for the Baseline 2017 scenario fall within a narrow range: $597.6 /t, $ 603.3/t and $610.2 /t for Japan, South Korea and Taiwan, respectively, indicated by the black dots in Figure 1(b). China managed to secure the most favorable import price terms at $650.8/t due to its significant import volumes and long-term pipeline delivery contracts.

Assuming that the price of oil imports is primarily defined by the global market rather than by bilateral

Figure 1(b): Efficient oil import frontiers: import price benefit.



Note: Black dots represent average monthly values observed in 2017.
Source: KAPSARC research.

contract terms, especially in the case of seagoing tanker imports, portfolio composition remains one of the most useful tools that oil importers can use for cost and risk management. Similar price benefit levels can yield significantly different risks, as is evident in the case of Japan compared to South Korea/Taiwan (Figure 1(b)).

South Korea and Taiwan had the most efficient import portfolios in terms of price/risk balance, according to the Baseline 2017 conditions. Although Taiwan's current position is slightly riskier than South Korea's, as represented in the chart by a higher standard deviation, the shape of Taiwan's efficient portfolio frontier curve suggests that it would be able to attain higher price benefits at a lower risk compared with South Korea, starting from about $635/t. China, on the other hand, has an efficient frontier curve that exponentially increases its risk level, starting from the price benefit measure of $580/t. If China's price benefit were closer to the price benefits observed for South Korea and Taiwan its portfolio risk would be within a similar range as South Korea and Taiwan's, i.e., significantly lower than currently observed.

Unlike the oil import volume frontier curves, the price benefit curves seem to be only partially affected by import diversification levels. The HHI for China's 2017 oil imports is 794, much lower than South Korea's (1495) or Taiwan's (1690), signifying that China has a more diversified portfolio. Yet South Korea and Taiwan demonstrated more efficient import price frontiers.

Based on the estimated parameters, for each importer we also computed the point where the frontier slope is equal to zero. This point represents

Table 2. Estimates of import growth and price benefit with uncertainty minimization condition (2017).

Importer	Oil import growth rate (%)	Price benefit ($/t)
China	1.43%	452
Japan	2.01%	335
South Korea	1.00%	359
Taiwan	1.59%	390

Source: KAPSARC.

the optimal return value, i.e., the oil import growth rate or price benefit measure when the risk level is minimized. The results of this counterfactual scenario are shown in Table 2; the corresponding frontier slopes and their sensitivity analysis are presented in Appendix 3.

The estimated risk-minimizing import growth rate values for China, Japan and South Korea are higher than those observed in 2017. This implies that these economies experienced a suboptimal level of oil import growth, demonstrating an overcautious approach to managing their import portfolios. Taiwan, conversely, significantly exceeded its risk-minimizing import growth threshold in 2017, signaling a more aggressive approach to managing its oil imports. The price benefit levels that minimize portfolio uncertainty are significantly lower than those observed in 2017 for all four economies studied. However, China has a notably higher risk-minimizing price benefit level compared with its peers, in line with its more beneficial price terms for 2017 oil imports.

A comparison of the efficient frontier curves of oil import volumes (Figure 1(a)) and oil import prices (Figure 1(b)) can provide insights into the trade-offs between supply security and associated costs and reveals the importers' energy security priorities. China, for instance, clearly emphasizes the security of its physical supply and is willing to take higher risks on price in its well diversified portfolio of oil imports. Taiwan, on the other hand, has structured its oil imports in a way that may minimize price risks but can lead to significant fluctuations in import volumes. Japan demonstrates comparable import volumes/risk efficiency for its oil imports but lags behind the three other East Asian importers' price/ risk efficiency. This implies that its overall oil import portfolio performance could be improved.

The observed differences in the efficient frontiers of the four oil importers studied in this paper demonstrate the applicability of an individual economy-based approach to global oil market portfolio strategy. The varying shapes and positioning of the curves suggest that factors affecting divergence extend beyond the differences in transportation costs. These patterns also show that there is no universal, efficient portfolio frontier for oil importers, even within the same geographic region.

Effects of changes in portfolio composition

To assess how reallocation of oil suppliers' shares impacts an importer's portfolio, we use the increased Saudi imports scenario, where the share of Saudi Arabian supplies in each of the four importers' portfolios is raised by 10% compared with the Baseline 2017 scenario. This amounts to approximately an additional 1.5 million tonnes of oil per month for the four importers. We fix the average import growth rates according to the Baseline 2017 scenario values by proportionally decreasing oil imports from other suppliers. In this simulation, we assess the impact of such portfolio restructuring on the risk component associated with imported volumes, the price benefit and its standard deviation. The results are shown in Table 3.

The results from this scenario indicate that increasing oil imports from Saudi Arabia at the expense of other suppliers would raise the volatility of import portfolios by around 20% for China, Japan and South Korea, and by 75% for Taiwan. It should be noted that Saudi Arabia had already secured a dominant share in the oil imports of most East Asian economies in 2017, accounting for 40.2% of Japan's oil imports that year, 29% of South Korea's and 31.4% of Taiwan's. China is the exception as it has vastly diversified the sources of its crude oil imports. This demonstrates that further enhancing the share of a major supplier magnifies market concentration levels and leads to higher volatility.

The negative impact on the supply security component, i.e., higher volatility, under this scenario is offset by a positive price effect for some

Table 3. Effects of increased oil imports from Saudi Arabia.

Importer	Energy security dimension	Parameter	Baseline 2017	Increased Saudi imports	
			Values	Values	% change
China	Volume	Growth rate	1.22	1.22	
		St. dev.	0.055	0.0667	21.3%
	Price	Price benefit	650.8	657.5	1.0%
		St. dev.	352.0	342.1	-2.8%
Japan	Volume	Growth rate	1.17	1.17	
		St. dev.	0.67	0.797	19.0%
	Price	Price benefit	597.6	597.5	0%
		St. dev.	429.8	511.6	19.0%
South Korea	Volume	Growth rate	0.26	0.26	
		St. dev.	0.53	0.647	22.1%
	Price	Price benefit	603.3	607.5	0.7%
		St. dev.	262.9	324.2	23.3%
Taiwan	Volume	Growth rate	4.37	4.37	
		St. dev.	0.798	1.397	75.1%
	Price	Price benefit	610.2	606.4	-0.6%
		St. dev.	272.1	367.4	35.0%

Note: St. dev. – Standard deviation.
Source: KAPSARC research.

importers. Price benefit levels increase for China by 1% and for South Korea by 0.7%. If China increases the volume of its oil imports from Saudi Arabia, this also leads to a reduction in the price volatility of its composite portfolio. The other three East Asian importers would see their price volatility increase, from a low of 19% for Japan to as high as 35% for Taiwan. Taiwan would also be the only importer to incur a negative effect on its portfolio price benefit.

These results suggest that changing the share of a particular supplier in a nation's oil import mix would yield significantly different outcomes for each importer. Increasing the market shares of suppliers, even those deemed most stable and reliable, such as Saudi Arabia (Downes 2011; Yicai Global 2017), can have both beneficial and detrimental impacts, depending on the individual portfolio composition and bilateral contract terms.

Portfolio resilience to external shocks

The efficient portfolio frontier model applied in this study also allows for assessment of how various external disruptions affect the performance of oil import portfolios. In this section, we consider the potential immediate and ensuing consequences of the strictly enforced oil exports embargo from Iran and the consequences of including the risk premium associated with passing through the Malacca Straits in the final oil import price.

We introduce two scenarios describing the potential consequences of a fully enforced Iranian oil embargo. First, we assume that imports from Iran are reduced to zero and that there is no redistribution of blocked imported volumes among other exporters: the Iranian Embargo scenario. In the second scenario, the Iranian oil imports remain withdrawn, but the associated volumes are proportionally reallocated among existing suppliers: the Iranian Replacement scenario. Under both scenarios, we estimate the impact on the imported oil volumes portfolios of the four East Asian countries under review. We do not assess the effect on the price benefit and its volatility, as an Iranian oil embargo would have, and indeed has had, a significant impact on the global oil price. Such a price shock would be a systematic, non-diversifiable risk, assessment of which lies outside of the scope of this study, rendering the diversifiable price risk peripheral. Table 4 presents the results of the Iranian embargo scenarios.

The impact of an interruption of oil shipments from Iran on this study's four East Asian importers would vary by economy. Table 4 shows that the volatility of Taiwan's crude oil import portfolio would increase by 3%, while China and Japan's Iran-related portfolio risk prices would rise by 8% and 9%, respectively. South Korea would be negatively impacted to the highest degree, with a 15.1% rise in its crude oil import portfolio volatility. These results correspond, to a certain extent, to the shares of Iranian crude in the four economies' respective total oil imports, by volume, in 2017: 3.1% for Taiwan, 7.2% for China, 5.5% for Japan, and 12.2% for South Korea. However, the impact also depends on the specific terms of Iranian shipments, i.e., price, regularity, and how they fit within the import portfolios of these four economies.

However, when the pre-embargo volumes shipped from Iran are redistributed among the remaining suppliers, the effect on the oil import portfolio of some of the four economies is reversed. The risk profiles of the Japanese and Taiwanese portfolios actually improve under this scenario, with their volatility reduced by 10% and 13%, respectively. The volatility of the Chinese import portfolio rises by 6.7%, compared with an 8% rise in the previous

Table 4. Immediate and ensuing impacts of the Iranian oil exports embargo.

Importer	Parameter	Baseline 2017	Iranian embargo		Iranian replacement	
		Values	Values	% change	Values	% change
China (volume)	Growth rate	1.22	1.24	1.6%	1.22	
	St. dev.	0.055	0.0594	8.0%	0.0587	6.7%
Japan (volume)	Growth rate	1.17	1.17	0.0%	1.17	
	St. dev.	0.67	0.73	9.0%	0.603	-10.0%
South Korea (volume)	Growth rate	0.26	0.26	0.0%	0.26	
	St. dev.	0.53	0.61	15.1%	0.594	12.1%
Taiwan (volume)	Growth rate	4.37	4.37	0.0%	4.37	
	St. dev.	0.798	0.822	3.0%	0.694	-13.0%

Note: St. dev. – Standard deviation.
Source: KAPSARC research.

scenario. However, the total substitution of Iranian imports would substantially increase South Korea's portfolio volatility under its current structure. It is therefore unsurprising that, among the countries studied, South Korea sought the maximum flexibility on waivers from the U.S. sanctions on Iran (Reuters 2018).

Finally, we estimate the effects of adding the risk premium to the price of oil imports that pass through the Malacca Straits. In the Malacca Straits risk premium scenario, we increase the price of the relevant oil imports by 10%, keeping all other inputs constant, as in the Baseline 2017 scenario. We assess the impact on the price parameters of each economy's oil import portfolio: the price benefit measure and corresponding standard deviation. Table 5 shows the results of the scenario.

Most of the Asian oil importers studied here would see their price benefit reduced within a range of between 5.2% (South Korea) to 5.8% (Japan). Such a price increase would, however, marginally reduce the standard deviation of their portfolios. China seems to be the most concerned about the risks associated with the Malacca Straits and is best positioned to develop alternative import routes. Its price benefit decrease of 2.6% would be less than that of other importers in the region. Due to its location and extensive import portfolio diversification

Table 5: Price effects of the Malacca Straits risk premium.

Importer	Parameter	Baseline 2017	Malacca Straits risk premium	
		Values	Values	% change
China (price)	Price benefit	650.8	633.6	-2.6%
	St. dev.	352.0	448.8	27.5%
Japan (price)	Price benefit	597.6	562.7	-5.8%
	St. dev.	429.8	339.7	-21.0%
South Korea (price)	Price benefit	603.3	571.7	-5.2%
	St. dev.	262.9	245.3	-6.7%
Taiwan (price)	Price benefit	610.2	576.3	-5.6%
	St. dev.	272.1	255.4	-6.1%

Note: St. dev. – Standard deviation.
Source: KAPSARC research.

efforts, China is less dependent on imports coming via the Malacca Straits than the other three economies in this study. Significant oil import volumes from Russia, the U.S., Kazakhstan and Vietnam, among others, bypass this route. However, even extensive oil import portfolio diversification would not mitigate a substantial 27.5% associated increase in its portfolio volatility under this scenario.

Conclusions

The security of physical supply and price affordability remain major elements of energy security, despite the recent expansion of the concept. The policies of energy importing economies emphasize security of physical supply and price affordability and the definitions of energy security adopted by international organizations also reflect these concerns. Rapidly shifting energy markets and changing global economic and geopolitical trends call for a methodology capable of evaluating the trade-offs between economic and security of supply considerations. Such a methodology should also account for the perspectives of individual importers and their bilateral relationships with suppliers and assess the impacts of potential vulnerabilities through scenario analyses.

This study demonstrates the benefits of applying financial portfolio theory to the topic of energy security. We estimate the efficient portfolio frontiers of crude oil imports and oil prices for the four big East Asian energy importers. The efficient frontier curves derived for China, Japan, South Korea and Taiwan allow us to assess their risk levels associated with particular oil import growth rates and prices. A comparison of the price benefit and import growth frontiers also provides insights into the four economies' current energy security priorities and the potential trade-offs they would face should they decide to amend their energy security strategies in terms of crude oil imports.

Our scenario analysis highlights the necessity of assessing energy security from the perspective of an individual importing country, taking into account the structure of its import portfolio, rather than analyzing the abstract uniform risks associated with suppliers, import routes or potential disruptions. Our simulations have shown that increasing the share of oil imports, even from the most reliable and stable suppliers, could be detrimental to a country's overall import portfolio. Depending on the structure of the portfolio, such an increase can result in more volatile import flows, represented by variance or standard deviation. An improvement in the average import price could come with an associated rise in volatility.

Potential disruptions associated with particular suppliers or import routes also demonstrate significantly varying impacts on energy importing economies. In the case of an effective Iranian oil export embargo scenario, the short-run portfolio risk increases across the board, albeit at different rates: from 3% for Taiwan to 15% for South Korea. However, when lost Iranian exports are substituted by other suppliers, some importers, including Japan and Taiwan, would see an improvement in the risk profiles of their energy import portfolios. Accounting for the 10% risk premium associated with shipments passing through the Malacca Straits would have only a moderate impact on China's oil import price levels compared with its regional peers, but would significantly increase the price volatility of its portfolio.

The scope of this study is limited to the short-term analysis of the four specified oil importing economies. However, the proposed framework can be used for long-term estimations and scenario analysis, using quarterly or annual import data. It can also be applied to the assessment of the energy security of traded fuels other than oil. It can also help exporters to optimize the portfolio of buyers based on their demand and price patterns. Potential areas for further research may include incorporating systemic and systematic risks, as well as integrating a risk assessment framework for events not observed in the past.

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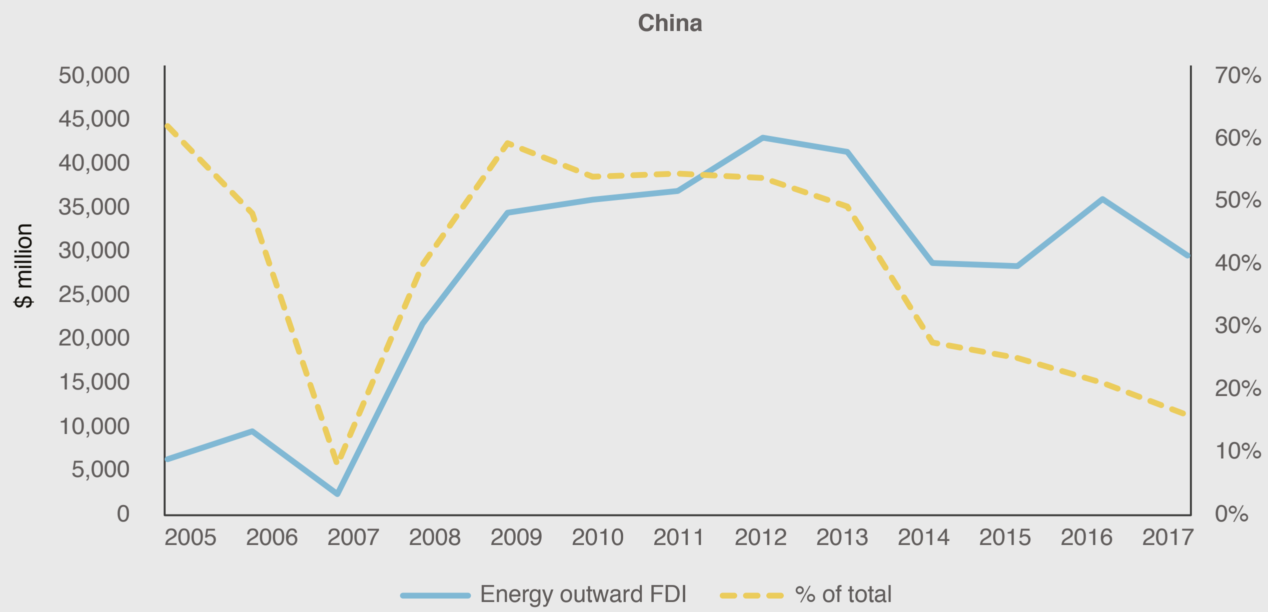
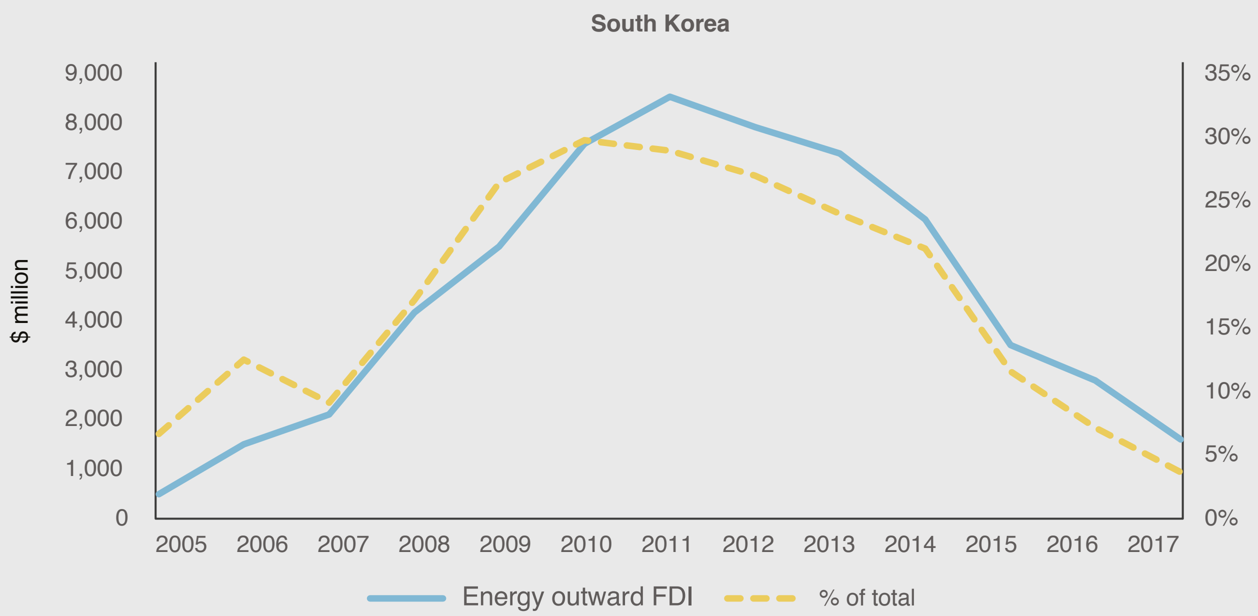
Appendix 1: Trends in Outward Direct Investment and East Asia's Energy Imports

Outward direct investment (ODI) in foreign energy assets can address the physical supply security component of energy security. The recent trend (see Figure A1) shows a decline in foreign direct investment in energy by major Asian energy importing economies.

Figure A1: Energy outward FDI flows from China and South Korea.



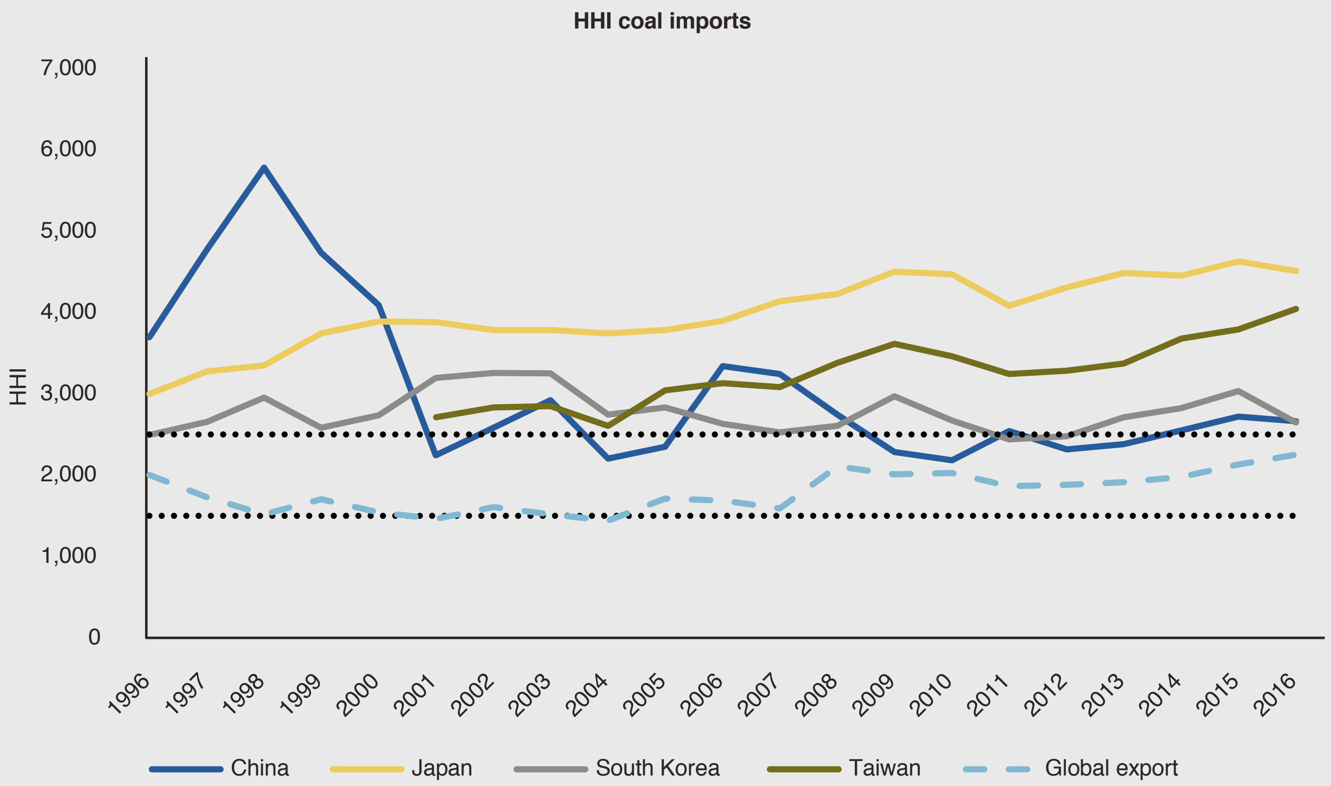


Sources: CEIC, American Enterprise Institute.

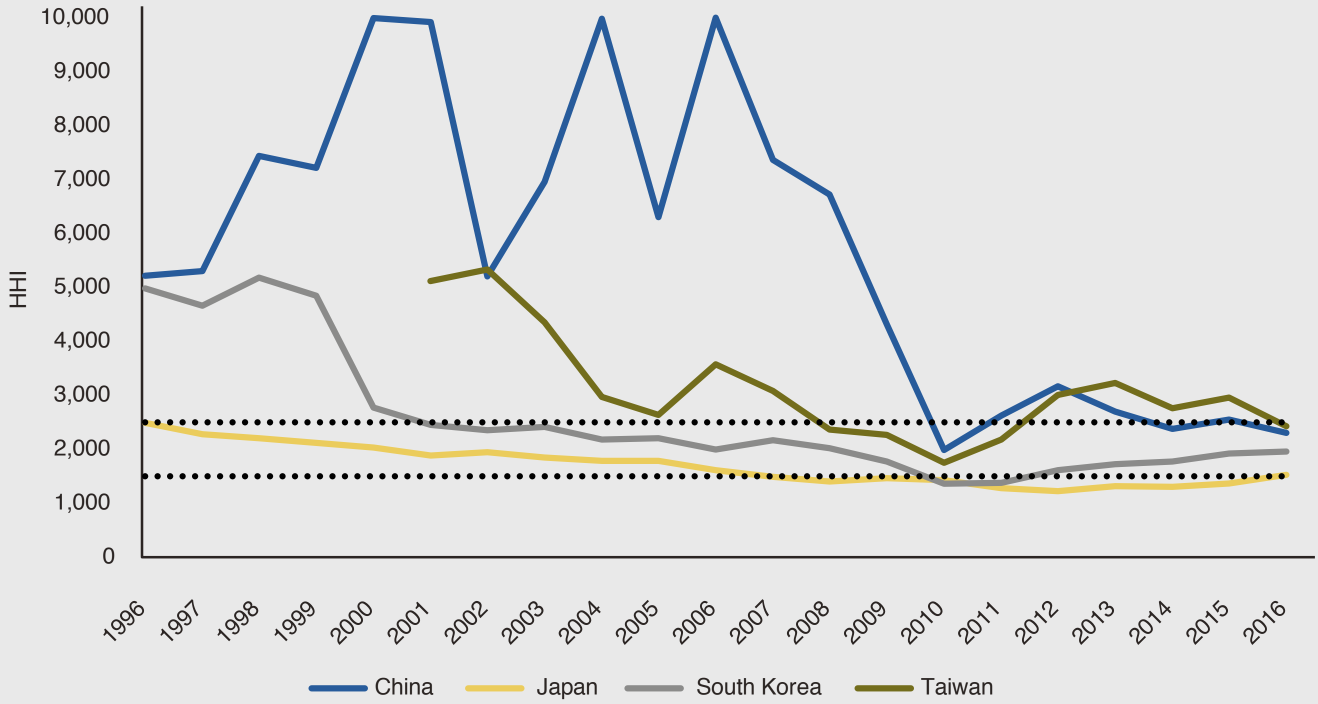
Appendix 1: Trends in Outward Direct Investment and East Asia's Energy Imports

The Herfindahl-Hirschman Index (HHI) is a common measure of market concentration that is used to determine market competitiveness. A market with an HHI below 1,500 is considered to be competitive, a market with an HHI between 1,500 and 2,500 is moderately concentrated, and a market with an HHI above 2,500 is highly concentrated. The HHI of fuel imports (Figure A2) shows the level of fuel import diversification for the four major East Asian energy importers.

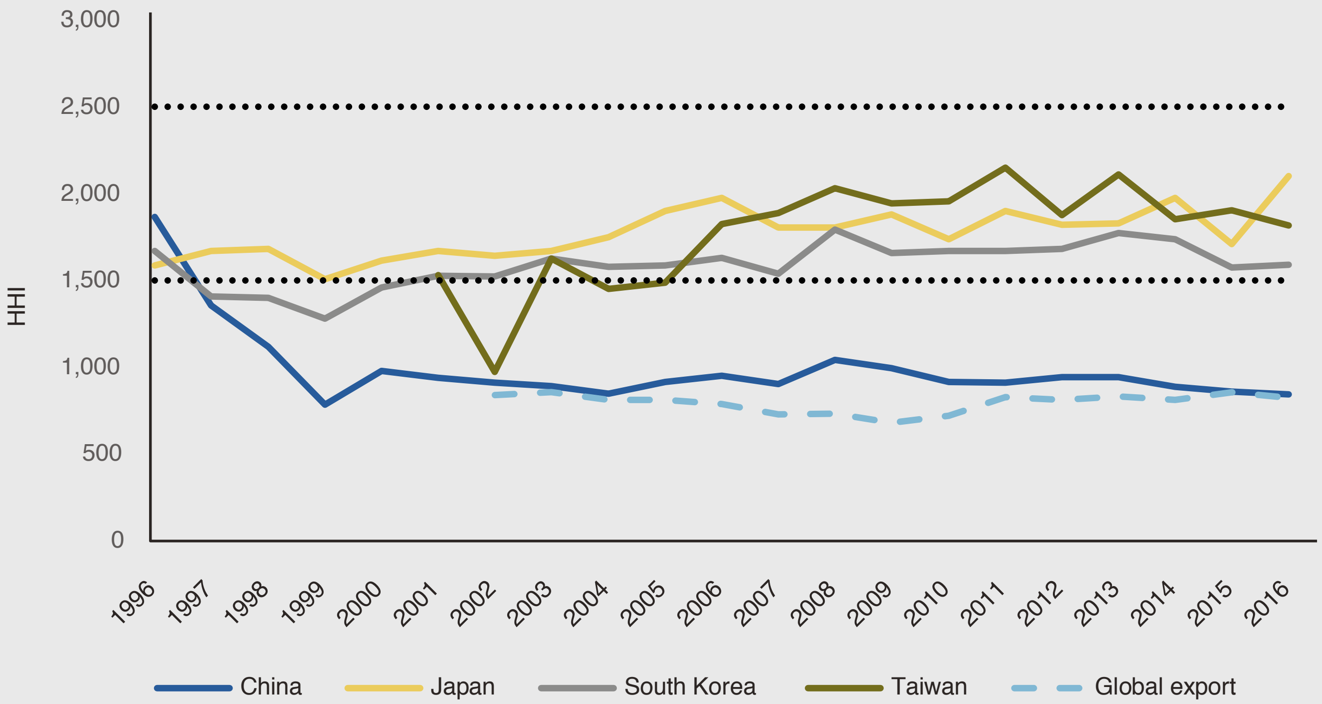
Figure A2. Herfindahl-Hirschman indexes of East Asian economies' fuel imports.



HHI gas imports



HHI oil imports



Sources: WITS, JODI.

Appendix 2: Estimation Method, Data, Model Output and Diagnostics

As with the Markowitz (1952) model, where investors minimize portfolio variance for a given level of expected return, we consider that oil imports are a portfolio choice that takes into account return and uncertainty. We investigate two aspects of oil imports: the physical imported volumes and the unit U.S. dollar import cost. In the first case, we consider the return as the overall import growth rate and uncertainty as the variability of the import growth rate across suppliers. In the second case, we consider the return as the price benefit associated with the oil imports and uncertainty as the variability of the price benefit across suppliers. For similar approaches applied to other sectors see Chandra (2003), Bigerna (2014), and Almusehyel and Alfawzan (2017).

Given these assumptions, the variance of the import growth rate to be minimized can be expressed as the weighted average of the covariance matrix of the individual inputs s'Vs, where V is the imports growth covariance matrix and s is an import shares vector. The total imports growth rate of i-th for economy g_i can be viewed as the sum of the import growth rates, weighted by each supplier's relative importance:

$$g_i = \Sigma_j s_j g_j \qquad (1)$$

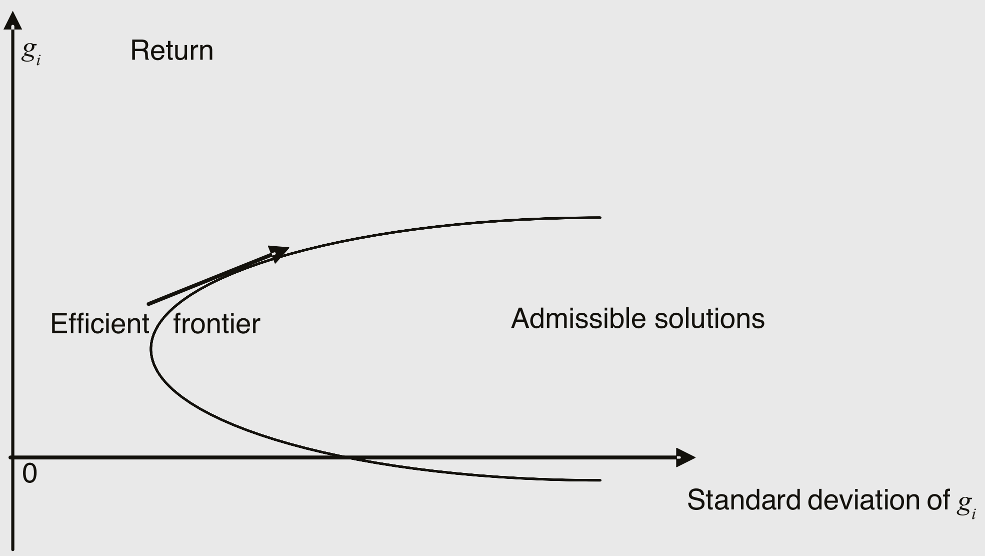
Standard optimization, which is formally given by min s'Vs, given the constraint: $\Sigma_j s_j g_j = g_i^*$ (g_i^* is the optimal growth rate), yields the relation between the minimum variance and its growth rate for different values of g_i^*. This yields the efficient frontier:

$$v^2_{gi} = (a\text{-}2bg_i + cg_i^2) / (ac - b^2) \qquad (2)$$

In Equation (2), a, b, c are the relevant parameters.

In the mean-standard deviation space, this latter equation defines a parabolic function of efficient portfolios, which represents the frontier of portfolios with minimum variance (see Figure A3).

Figure A3. The Standard Efficient Portfolio Frontier.



Source: KAPSARC.

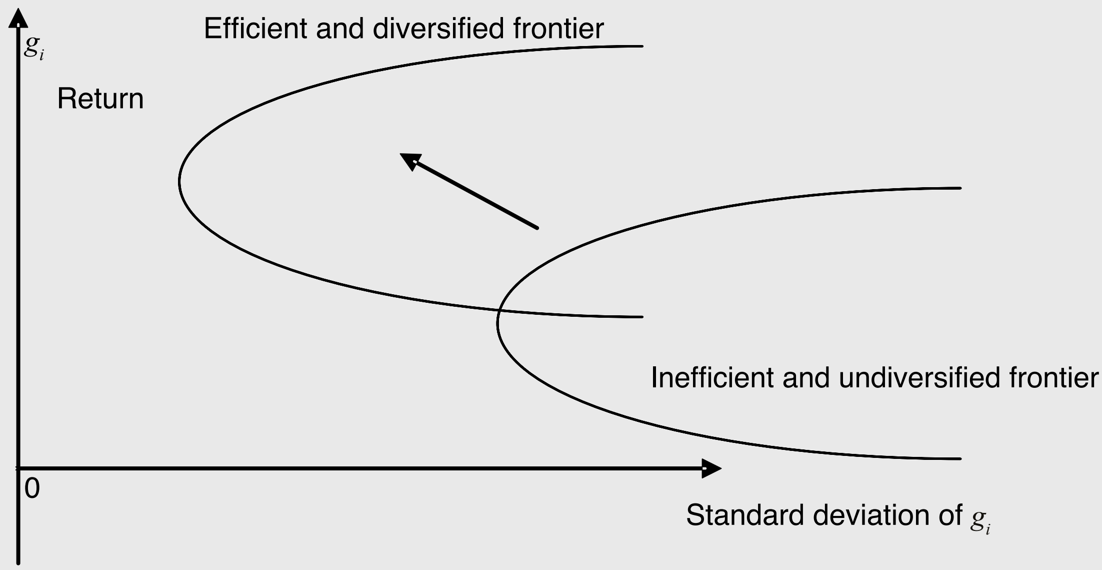
In the first case, the return variable defined by the oil imports growth rate of an economy and the variance defined by the structural composition or diversification of its imports represent a trade-off between high growth and concentration or the diversification of the supply structure. An importer that prefers a narrow range of high growth suppliers faces a higher risk of a downturn in the event of exogenous disruptions. Similarly, the second case represents a trade-off between focusing on the most profitable suppliers and diversifying to reduce supplier-specific risks. Hence, this approach covers the security of physical supply and price affordability components of energy security.

A frontier can be positioned toward the upper left or lower right, as shown in Figure A4. A shift to the left implies more diversification (lower uncertainty); combined with the upward movement, it represents a more efficient and diversified portfolio.

A frontier can also move toward the lower left or upper right segments, as shown in Figure A5. The lower left segment represents a risk-minimizing diversification with higher associated costs, while the upper right implies a more unstable value-maximizing behavior. Movements up and to the right show a shift toward a higher return and a higher risk.

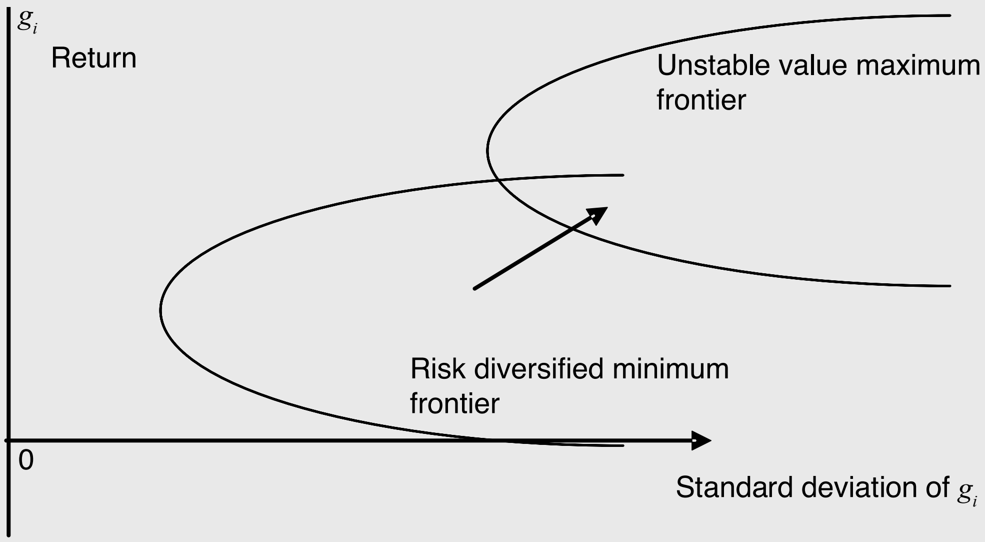
Our analysis of these trade-offs focuses on the four major oil importers in the East Asia region: China, Japan, South Korea and Taiwan. To construct efficient portfolio frontiers, we use the oil import data of these economies, disaggregated by suppliers. Oil imports are recorded at the monthly frequency in physical terms (tonnes) and value terms (U.S. dollars [$] on cost insurance and freight [CIF] basis). We derive the monthly average unit price as the

Figure A4. An efficient and diversified portfolio.



Source: KAPSARC.

Figure A5: Value maximization and risk minimization strategies.



Source: KAPSARC.

ratio of associated imported values to quantities. Data are aggregated for each importing economy studied for a specified period T and a specified number of suppliers M. The resulting dataset can be described as follows:

T_{China} = (2005:1-2017:12); M_{China} = 76.
T_{Japan} = (2001:5-2017:12); M_{Japan} = 51.
$T_{South\ Korea}$ = (2002:1-2017:12); $M_{South\ Korea}$ = 23.
T_{Taiwan} = (2006:1-2017:12); M_{Taiwan} = 39.

For the variable of flows in physical terms, we compute monthly growth rates and associated standard deviations for each supplier.

For the variable of flows in dollar terms, we compute a measure of the price benefit associated with each supply source, defined as $1,000 minus the unit price.

For the purpose of empirical estimation, we simplify Equation (2) to obtain a relationship between the standard deviation with the return and return squared, expressed as follows:

$$SD_t = a + b_1 g_t + b_2 g_t^2 + e_t \qquad (3)$$

where SD_t is the standard deviation of the i-th oil import flows or of the i-th price benefit, a is the fixed effect, g_t is the annual growth rate of the total flow or the average profitability index, and e_t captures the residual error.

We first test for the cointegrating properties of the series, applying the Dickey-Fuller and the Engle-Granger tests, as shown in Table A1. The cointegration tests that we apply to avoid the risk of spurious correlation when running the regression show that the growth variables are generally stationary and that cointegration relations exist.
To test for the normality of the return, we have run Jarque-Bera tests (a joint Lagrange multiplier test of the residuals' skewness and kurtosis) on growth returns and the price benefit for the four economies. We find no serious indication of non-normality (not reported herein but available upon request).

Table A1. Cointegration analysis.

China

Oil import growth rate				**Oil price benefit**			
Test	SDEV	SG	SGSQ	Test	SDEV	SG	SGSQ
Wtd.sym.	-4.57299	-4.63067	-6.29985	Wtd.sym.	-6.61586	-3.32025	-3.73141
Dickey-F	-4.42484	-5.74684	-7.50091	Dickey-F	-6.44679	-3.18084	-3.64723
P-values				P-values			
Wtd.sym.	0.0008	0.0007	0.0000	Wtd.sym.	0.0000	0.0344	0.0103
Dickey-F	0.0020	0.0000	0.0000	Dickey-F	0.0000	0.0883	0.0261
Num.lags				Num.lags			
Wtd.sym.	5	8	3	Wtd.sym.	2	3	3
Dickey-F	5	8	4	Dickey-F	2	3	3
Engle-Granger				Engle-Granger			
TestStat	P-value	Num.lags		TestStat	P-value	Num.lags	
-4.49307	0.0172	5		-6.49644	0.0000	2	

South Korea

Oil import growth rate				**Oil price benefit**			
Test	SDEV	SG	SGSQ	Test	SDEV	SG	SGSQ
Wtd.sym.	-5.88235	-6.6993	-6.50378	Wtd.sym.	-5.88235	-6.6993	-6.50378
Dickey-F	-5.72407	-6.73635	-6.36048	Dickey-F	-5.72407	-6.73635	-6.36048
P-values				P-values			
Wtd.sym.	0.0000	0.0000	0.0000	Wtd.sym.	0.0000	0.0000	0.0000
Dickey-F	0.0000	0.0000	0.0000	Dickey-F	0.0000	0.0000	0.0000
Num.lags				Num.lags			
Wtd.sym.	2	5	4	Wtd.sym.	2	5	4
Dickey-F	2	5	5	Dickey-F	2	5	5
Engle-Granger				Engle-Granger			
TestStat	P-value	Num.lags		TestStat	P-value	Num.lags	
-5.78186	0.0001	2		-5.78186	0.0001	2	

Japan

Oil import growth rate				**Oil price benefit**			
Test	SDEV	SG	SGSQ	Test	SDEV	SG	SGSQ
Wtd.sym.	-5.9152	-5.85848	-5.03217	Wtd.sym.	-1.87872	-2.03346	-1.61885
Dickey-F	-5.76384	-5.76453	-4.92098	Dickey-F	-1.71236	-1.5368	-1.53231
P-values				P-values			
Wtd.sym.	0.0000	0.0000	0.0002	Wtd.sym.	0.7261	0.6254	0.8521
Dickey-F	0.0000	0.0000	0.0002	Dickey-F	0.7454	0.8162	0.8178
Num.lags				Num.lags			
Wtd.sym.	5	12	12	Wtd.sym.	6	5	8
Dickey-F	15	12	12	Dickey-F	6	8	8
Engle- Granger				Engle-Granger			
TestStat	P-value	Num.lags		TestStat	P-value	Num.lags	
-5.78186	0.0001	5		-5.45109	0.0005	4	

Taiwan

Oil import growth rate				**Oil price benefit**			
Test	SDEV	SG	SGSQ	Test	SDEV	SG	SGSQ
Wtd.sym.	-6.82379	-8.38558	-8.36571	Wtd.sym.	-4.71745	-3.17694	-3.79913
Dickey-F	-5.42525	-8.30428	-8.2467	Dickey-F	-4.65543	-3.03879	-3.68666
P-values				P-values			
Wtd.sym.	0.0000	0.0000	0.0002	Wtd.sym.	0.0005	0.0519	0.0085
Dickey-F	0.0000	0.0000	0.0002	Dickey-F	0.0008	0.1216	0.0233
Num.lags				Num.lags			
Wtd.sym.	2	4	3	Wtd.sym.	2	4	3
Dickey-F	3	4	3	Dickey-F	2	4	3
Engle-Granger				Engle-Granger			
TestStat	P-value	Num.lags		TestStat	P-value	Num.lags	
-6.49044	0.0001	2		-6.39239	0.0001	2	

Notes:
SDEV: Standard deviation
SG: Return
SGSQ: Return squared
Wtd.sym.: Weighted symmetric test
Dickey-F: Dickey-Fuller test
Engle-Granger: Engle-Granger test
Num.lags: number of lags

Source: KAPSARC research.

We then test the validity of the assumption of convexity of the portfolio frontiers. Table A2 lists the significance, sign and magnitude of the estimated coefficient values b_1 and b_2 during the period of estimation. Estimation results generally conform to the theory: the first coefficient (b_1) is negative and the second (b_2) is positive. The Durbin-Watson test results are acceptable. The significance value of the coefficient b_2 is important when assessing the pattern of diversification. A coefficient value significantly greater than unity shows an importer's diversification increasing. The empirical results show increasing diversification only for South Korea's crude oil import quantity growth rate.

Table A2. Estimation results.

China				
Oil imports growth rate				
Number of observations: 154				
Mean of dep. var. = .048086		LM het. test = 4.42708 [.035]		
Std. dev. of dep. var. = .121959		Durbin-Watson = 1.93455 [<.672]		
R-squared = .037179		Schwarz B.I.C. = -83.7440		
Adjusted R-squared = -.022997		Log likelihood = 108.929		
Variable	coefficient	Std.error	t-statistic	P-value
B1	-.106115	.086362	-1.22873	[.221]
B2	.075642	.015987	4.73155	[.000]
Oil price benefit				
Number of observations: 154				
Mean of dep. var. = 322.457		LM het. test = 5.66136 [.017]		
Std. dev. of dep. var. = 469.242		Durbin-Watson = 2.13967 [<.936]		
R-squared = .048857		Schwarz B.I.C. = 1181.58		
Adjusted R-squared = .325413E-02		Log likelihood = -1161.43		
Variable	coefficient	Std.error	t-statistic	P-value
C	671.819	239.335	2.80702	[.006]
B1	-1.75641	1.21823	-1.44177	[.152]
B2	.194376E-02	.140912E-02	1.37942	[.170]

Appendix 2: Estimation Method, Data, Model Output and Diagnostics

South Korea

Oil imports growth rate

Number of observations: 119

Mean of dep. var. = .861939	LM het. test = 13.6191 [.000]
Std. dev. of dep. var. = 1.41083	Durbin-Watson = 1.67730 [<.087]
R-squared = .112209	Schwarz B.I.C. = 214.175
Adjusted R-squared = .081059	Log likelihood = -202.227

Variable	coefficient	Std.error	t-statistic	P-value
C	14.9663	11.0752	1.35134	[.179]
B1	-28.9548	22.0840	-1.31112	[.192]
B2	14.5236	10.9516	1.32616	[.187]

Oil price benefit

Number of observations: 119

Mean of dep. var. = 173.382	LM het. test = .432472 [.511]
Std. dev. of dep. var. = 89.1313	Durbin-Watson = 1.71630 [<.069]
R-squared = .985338	Schwarz B.I.C. = 460.820
Adjusted R-squared = .985213	Log likelihood = -456.032

Variable	coefficient	Std.error	t-statistic	P-value
C	289.813	152.668	1.89832	[.066]
B1	-.445969	.474438	-.939994	[.354]
B2	.665103E-03	.366426E-03	1.81511	[.079]

Japan

Oil imports growth rate

Number of observations: 198

Mean of dep. var. = .717352	LM het. test = 3.74006 [.053]
Std. dev. of dep. var. = .351954	Durbin-Watson = 2.03477 [<.715]
R-squared = .125371	Schwarz B.I.C. = 73.6509
Adjusted R-squared = .107244	Log likelihood = -60.4303

Variable	coefficient	Std.error	t-statistic	P-value
B1	-.658568	.212517	-3.09889	[.002]
B2	.661404	.025644	25.7915	[.000]

Oil price benefit

Number of observations: 108

Mean of dep. var. = 288.381	LM het. test = .377540 [.539]
Std. dev. of dep. var. = 101.809	Durbin-Watson = 2.02497 [<.707]
R-squared = .966365	Schwarz B.I.C. = 480.565
Adjusted R-squared = .965059	Log likelihood = -468.859

Variable	coefficient	Std.error	t-statistic	P-value
C	481.326	8.71664	55.2192	[.000]
B1	-.515816	.055616	-9.27463	[.000]
B2	.718015E-04	.724519E-04	.991023	[.324]

Taiwan

Oil imports growth rate

Number of observations: 192

Mean of dep. var. = .829697		LM het. test = 1.09557 [.295]		
Std. dev. of dep. var. = .457813		Durbin-Watson = 1.73390 [<.107]		
R-squared = .217978		Schwarz B.I.C. = 119.353		
Adjusted R-squared = .188227		Log likelihood = -98.3228		
Variable	coefficient	Std.error	t-statistic	P-value
C	.342693	.206697	1.65794	[.099]
B1	-.552038	.467155	-1.18170	[.239]
B2	.439809	.191908	2.29177	[.023]

Oil price benefit

Number of observations: 96

Mean of dep. var. = 175.780		LM het. test = 7.38212 [.007]		
Std. dev. of dep. var. = 106.461		Durbin-Watson = 1.82639 [<.429]		
R-squared = .307558		Schwarz B.I.C. = 582.156		
Adjusted R-squared = .260877		Log likelihood = -566.180		
Variable	coefficient	Std.error	t-statistic	P-value
C	363.836	40.2776	9.03321	[.000]
B1	-.401999	.202373	-1.98642	[.049]
B2	.515470E-04	.532341E-04	.968859	[.125]

Notes:
Mean of dep. var.: Mean of dependent variable
LM het.test: Lagrange multiplier heteroskedasticity test
Std. dev. of dep. var.: Standard deviation of dependent variable
Durbin-Watson: Durbin-Watson test
Schwarz B.I.C.: Schwarz's bayesian information criteria
Std.error: Standard error

Source: KAPSARC research.

Appendix 3: Returns and Frontier Slopes Under Risk Minimization

Table A3. Estimates of the uncertainty-minimizing growth rate of oil imports.

Importer	Oil import growth rate	Frontier slope	Frontier slope for different values of growth		
			g=1%	g=2%	g=3%
China	1.43%	0.151g-0.106	0.045	0.121	0.196
Japan	2.01%	1.323g-0.659	0.664	1.326	1.987
South Korea	1.00%	0.291g-0.289	0.001	0.146	0.291
Taiwan	1.59%	0.880g-0.552	0.328	0.767	1.207

Note: coefficient values are taken from Table A2 in Appendix 2; g represents the growth rate of oil imports.
Source: KAPSARC research.

Table A4: Estimates of the uncertainty-minimizing oil import price benefit.

Importer	Price benefit, $/t	Frontier slope	Frontier slope for different values of the price benefit		
			p=500	p=600	p=700
China	452	0.00389p-1.756	0.19	0.58	0.96
South Korea	335	0.00133p-0.445	0.22	0.35	0.49
Japan	359	0.00144p-0.516	0.20	0.35	0.49
Taiwan	390	0.00082p-0.402	0.01	0.09	0.18

Note: coefficient values are taken from Table A2 in Appendix 2; p represents the price benefit associated with oil imports.
Source: KAPSARC research.

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About the Project

This project will assess how the concept of energy security and the energy security strategies of suppliers and consumers have evolved following recent shifts in global energy markets, such as increasing fungibility of energy, higher degree of interconnectivity of regional fuel markets and rapid deployment of renewables. It studies the implications and potential directions of these evolutions, with a focus on the economies of the Gulf Cooperation Council (GCC) and Northeast Asia. The project investigates the collaboration between economies in both regions, with an emphasis on Saudi Arabia and China. It sets out to identify the key drivers of the new energy security paradigm, from the perspectives of both suppliers and consumers.

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