Examining Network Structures and Dynamics of World Energy Companies in Stock Markets: A Complex Network Approach

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ABSTRACT

The energy sector occupies a mainstay role in overall growth in the modern worldwide economy. Therefore, it is essential to examine network structures and dynamics of leading energy companies of the world through complex network methods. Because, complex network methods are significant tools of studying the static and dynamics properties of the stock market, which allows us to better comprehend the stock market. We use daily prices of 147 energy stocks belonging to 34 countries of the world from 2006-2019. In addition to the overall sample, we explore networks for two sub-periods to examine the topological evolution during global recession of 2008, and energy and European debt crisis of 2011. Our results show substantial clustering of energy companies based on their geographic position during overall sample period. However, the crisis periods lead to a break in Asian and European clusters and only one prominent cluster appears in all the periods belonging to North American energy companies. We also observe few top US and European based companies occupying important and great global influence positions in the networks. In addition, time-varying topological measures indicate contraction of networks during crisis time, and an expansion in the recovery periods. More implications are also discussed.

Keywords: Energy Companies, Complex Network, Threshold Network, Minimum Spanning Tree, Stock Market, Crisis

JEL Classifications: C18, E32, E44, G01, G14, G15, G19

1. INTRODUCTION

In today’s world, countries rely heavily on the consumption of energy to increase their industrial production and to boost their economic growth. The EIA (US energy information administration) has projected a growth in the world energy consumption by 28% between 2015 and 20401. Simultaneously, a constant growth in the overall energy consumption of 2.3% is observed in the year 2018, led by China with an overall energy consumption growth of 3.7%2. Previous work explores the relationship among the development and energy use of a country (Alam et al., 1998; Dias et al., 2006; Apergis and Payne, 2011; Lambert et al., 2014; Arto et al., 2016). They found strong correlations among energy use and living standards. Therefore, further understanding of worldwide energy companies, interaction, and evolution of network structures is of vital importance to investors and policy makers since stocks markets and energy companies to be specific have become much more integrated.

Although globalization and expansion of economic activities resulted in optimum allocation of economic resources in the financial markets, it simultaneously encourages a rapid spread of financial crises that can topple the world financial system. Such as, the 2008 financial crisis, that shook the world economic and financial system within no time. Many studies attempt to analyze the impacts of financial crisis 2008 on stock market networks. Gong et al. (2019) observed an increase in the network

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1 Please see: https://www.eia.gov/todayinenergy/detail.php?id=32912
2 Please see: https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html
connectedness of global stock markets during financial crisis of 2008. Similarly, a substantial increase in the average correlations during financial crisis time period of 2008 has been observed for US stock market (Qiu et al., 2018), Pakistan stock market (Memon and Yao, 2019), Chinese stock market (Ren and Zhou, 2014), South African stock market (Majapa and Gossel, 2016), and Korean stock market (Nobi et al., 2014). Therefore, market participants actively require better understanding of the correlations in complex financial market systems.

The world energy companies network can be regarded as a complex network. In the past, researchers occasionally use correlation analysis to develop stock market networks, by considering stocks as nodes of the networks and pairwise interaction among prices of stocks as their respective edges. The correlation-based networks have emerged as a useful tool to define static and dynamic properties of the network (Nobi et al., 2014; Jo et al., 2018; Lee and Nobi, 2018; Li and Pi, 2018; Memon and Yao, 2019; Yao and Memon, 2019). Particularly, with Pearson cross-correlation network method, we can perceive topological properties of the threshold network (TN), produced by assigning a value of threshold (Lin et al., 1994; Boginski et al., 2005), the asset graph (AG) (Onnela et al., 2003; Onnela et al., 2003), the minimum spanning tree (MST) (Mantegna, 1999; Mantegna and Stanley, 2000), and the planar maximally filtered graph (PMFG) (Tumminello et al., 2005; Song et al., 2011). Clearly, Pearson correlation-based network methods have been extensively applied to numerous financial systems (Onnela et al., 2004; Kwapień et al., 2009; Coletti, 2016; Mai et al., 2018; Memon et al., 2019; Zięba et al., 2019; Memon et al., 2020), and is thus used in this paper.

Unlike most studies that primarily focuses on the network structure and evolution of either world stock markets indices (Lee and Nobi, 2018; Li and Pi, 2018; Sensoy and Tabak, 2014), or local stock markets (Memon and Yao, 2019; Yao and Memon, 2019; Nobi et al., 2014; Wilinski et al., 2013), this paper explores the state, network structure, and dynamics of well-known world energy companies. In the summary, this paper has made three main contributions. First, our study extends financial network literature by focusing on 147 most popular energy companies belonging to 34 countries of the world, using a dataset spanning over wide period of nearly 14 years. Secondly, previous research focuses solely on the econometric techniques for energy stocks. Therefore, we attempt to apply complex network methods to analyze network structures of energy companies of the world, for the 1st time. Additionally, our study is a comparative work that explore and compare network structures at two crucial time periods of Global financial crisis in the year 2008, and Oil prices spike in the year 2011. Thirdly, the results presented in our study and understanding of the correlation structure and dynamics of popular energy companies of the world is important for a wide range of market participants including: local investors, multinational corporations, and regulators or policy makers worldwide.

The paper is organized as follows. Section 2 provides a review of the relevant literature. Section 3 presents the data and methodology of constructing threshold networks, MST, and weighted network measures. Section 4 show results and discusses them. Finally, Section 5 concludes the paper.

2. LITERATURE REVIEW

The existing literature offers numerous stock market correlation-based networks to determine its possible structure. For example, (Tang et al., 2018) examined companies listed in two stock markets of China securities index 300 and Standard & Poor’s 500 between 2007 and 2015. In addition to the identification of stock connectedness in the MST network, their results also revealed similar topological properties for an emerging market of CSI300, and a mature well-developed stock market of S&P500. Kantar et al. (2012) analyzed topological properties of top 50 Turkish companies over the period of 2006 to 2010, and their results showed less influence of financial crisis 2008 on the Turkish market. In contrast, (Memon and Yao, 2019; Sensoy and Tabak, 2014; Coletti and Murgia, 2016) found contraction or shrinkage of the network structure during crises. Moreover, (Gałązka, 2011) investigated polish stock market network after applying MST method between January and December 2007. His results showed few hub companies in the network that can influence the price dynamics of other companies in the stock market.

Regarding network analysis for world oil market, (Jia et al., 2017) applied wavelength based complex network methods to study structural characteristics of 26 groups of oil prices in the world oil market between June 1999 and March 2011. In addition to identifying the global oil market integration, their results also showed prominent role of some regional markets due to the emergence of two big groups of regional markets in the network. Ji and Fan (2016) applied MST and confirmed integration among world crude oil market using weekly oil price data of 24 countries between 2000 and 2011. Li et al. (2019) studied spillover effects among oil and gas markets using complex network method. Their results revealed key correlation patterns and transmission relations by some network indicators.

A large set of methods has been used in exploring the relationship among stock markets and oil prices. Zhang and Liu (2018) applied dynamic copula and VAR-DAG models between 2000 and 2017 to examine oil stock contagion and its propagation in seven countries stock markets. Additionally, (Ahmadi et al., 2016) used structural vector autoregressive (SVAR) and found different responses to oil price shocks on the US stock market returns. Lin and Tsai (2019) found six structural breaks in the oil price due to major global events by applying structural change testing models and autoregressive distributed lag and error corrective model (ARDL-ECM). They directed investor attentions towards political and economic impacts on oil prices, combing with market fear gauge and the way it can affect oil prices. Wei and Guo (2017) studied the impact of oil price shocks on Chinese stock market between February 1996 and October 2015 by employing structural VAR model. They found that demand-oriented speculations related to oil prices have significant effects on China stock market. Moreno and Pereira da Silva (2016) used multifactor market models on Spanish stock market over the period of 2008-2015. Their results found significant positive and negative impacts of European Union ETS.
on stock market returns of Spanish companies in various phases. Using a GARCH based model, (Schaeffer et al., 2012) examined the impact on market value of oil companies that followed Dow Jones Sustainability Index (DJSI). Their empirical results show no change between volatility and linkage of oil companies with the oil price. While applying similar model, (Dutta et al., 2017) established a link between oil volatility index (OVX) and eleven Middle east and African stock markets. They found significant impact of OVX on the mean and volatility of majority Middle East and African stock returns.

Network analysis has also been introduced to analyze the relationship between renewable energy companies of the world. For instance, (Kazemilari et al., 2017) applied the MST to study 70 stocks of renewable energy companies over the time period of October 2010-March 2015. In addition to highlighting important nodes of the network, they also found significant role of these nodes for the development of renewable energy market. In addition, (Kazemilari et al., 2019) also investigated sectorial behavior pattern of 60 renewable energy companies listed in American stock market between July 2015 and January 2018. Their results showed association of stocks to their particular sector. Regarding energy markets, (Lautier and Raynaud, 2012) used 12 years data of daily futures returns to examine systematic risk in the energy derivative market. Their findings exhibited energy markets holding central position in the overall system. From literature, we can extract importance of the application of network-based methods due to its extensive use. It is also evident that there is a need to extract information of the important nodes, structural changes, and topological properties of energy companies of the world, due to the lack of literature in this domain.

3. DATA AND METHODOLOGY

3.1. Data

Over the past, the stock markets throughout the world have experienced several crises, including the global financial crisis 2008, and oil price shocks combined with European debt crisis of 2011, etc. Therefore, the time period we have chosen for the network analysis of energy companies starts from January 03, 2006 to June 28, 2019, covering all such events. Additionally, there are several energy companies in the world. Our study attempts at gathering the data of well-known energy companies of the world. Table A1 highlights websites for popular energy companies of the world. To sum up, we evaluate daily closing prices of 147 well known energy companies from 34 countries over the time period 2006 to 2019. We construct network of N=147 using correlation distances among closing stock prices obtained from http://finance.yahoo.com. Table 1 lists 147 energy companies, acting as nodes in the network (differentiated with a unique ID), and categorized by their respective sector and country.

3.2. Methodology of Network Construction

We describe the daily energy stock returns $i$ to be $r_i(t)=\ln P_i(t)-\ln P_i(t-1)$, where $P_i(t)$ is the price of $i$ stock at time $t$ and $t-1$, respectively. The interrelations between two stocks $i$ and $j$ are formed through correlation coefficient $C_{ij}$, and is defined as:

$$C_{ij} = \frac{r_i r_j - \langle r_i \rangle \langle r_j \rangle}{\sqrt{\langle r_i^2 \rangle - \langle r_i \rangle^2} \sqrt{\langle r_j^2 \rangle - \langle r_j \rangle^2}} \quad (1)$$

Where $r_i$ and $r_j$ symbolize return time series of stock $i$ and $j$, and $\langle r_i \rangle$ represents its mean value over the time period under investigation. In our study, there are N=147 energy companies of the network, the correlation matrix $C$ highlights summary of complex system among the 147 (147-1)/2 pair of stock components. Additionally, the elements of correlation matrix $C_{ij}$ ranges from $-1$ to 1, where a positive value of $C_{ij}>0$ indicates the two stocks fluctuate in a positively correlated manner, and a negative value $C_{ij}<0$ represents the two stocks fluctuate in an anticorrelated way. However, if $C_{ij}=0$ means two stocks are uncorrelated, and if $C_{ij}=1$ represents two stocks are perfectly correlated. From here, we can easily form a threshold network $\theta$, by providing a specific value $\theta$, ($-1 \leq \theta \leq 1$), from cross-correlation coefficients. Such as, if $C_{ij}>\theta$ between two stocks, an undirected edge is drawn. Clearly, at certain threshold $\theta$, one can obtain various set of links (Lee and Nobi, 2018).

Thereafter, we convert correlation matrix $C_{ij}$ into distance matrix $d_{ij}$ among stocks $i$ and $j$. It is defined as (Mantegna, 1999):

$$d_{ij} = \sqrt{2(1-C_{ij})} \quad (2)$$

Where distance matrix $d_{ij}$ deviates from 0 to 2 between stocks $i$ and $j$, and the minimum spanning tree (MST), represented as $T$, can be computed by applying (Kruskal, 1956) algorithm, as follows:

$$T = \sum_{\{(i,j) \in T\}} d_{ij} \quad (3)$$

3.3. Network Topology Measures

Our study applies numerous network measures to examine network static properties and dynamics at various partitions. Node degree refers to the direct connections and linkages a certain node has in the overall network. It is calculated as follows:

$$k_i = \sum_{j=1}^{N} a_{ij} \quad (4)$$

Where $k_i$ is the degree of node $i$, $N$ is the size of the network, and $a_{ij}$ is the number of links among stocks $i$ and $j$. Further, to detect the modularity of threshold network at different intervals, we apply following definition (Newman, 2006):

$$Q = \frac{1}{4m} \sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m}\right) \delta_{c_i c_j} \quad (5)$$

In the above formula $\delta_{c_i c_j}$ represents community consists of nodes $i$ and $j$.
Table 1: 147 energy stocks from 34 countries of the world are included in our data sample. In the table, we mention unique ID of the stock, stock ticker, company name, sector & Industry code, and their respective country and continent name

| ID  | Stock Ticker | Company Name                        | Sector              | Industry Code                  | Industry Code                  | Country     | Continent |
|-----|--------------|-------------------------------------|---------------------|--------------------------------|--------------------------------|-------------|-----------|
| Z1  | ACE.MI       | Acea SpA                            | Utilities           | Utilities                       | Utilities                       | Italy       | Europe    |
| Z2  | AEP          | American Electric Power Company     | Utilities           | Utilities                       | Utilities                       | United States | North America |
| Z3  | AOL.TO       | Africa Oil Corp.                     | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | Canada      | North America |
| Z4  | APA          | Apache Corp                          | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z5  | APC          | Anadarko Petroleum Corp              | Energy              | Oil & Gas Integrated           | Oil & Gas Integrated           | United States | North America |
| Z6  | BEP          | Brookfield Renewable Partners        | Utilities           | Utilities                       | Utilities                       | Canada       | North America |
| Z7  | B博士        | Baker Hughes                        | Energy              | Oil & Gas Equipment & Services | Oil & Gas Equipment & Services | United States | North America |
| Z8  | BIR.TO       | Birchcliff Energy Ltd                | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | Canada       | North America |
| Z9  | 600578.SS    | Beijing Jingpeng Power Co Ltd       | Utilities           | Utilities                       | Utilities                       | China       | Asia      |
| Z10 | BPLC.NS      | Bharat Petroleum Corp               | Energy              | Oil & Gas Refining & Marketing | Oil & Gas Refining & Marketing | India       | Asia      |
| Z11 | BP.L         | BP plc                              | Energy              | Oil & Gas Integrated           | Oil & Gas Integrated           | UK          | Europe    |
| Z12 | CEO          | CNOOC Limited                       | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | China       | Asia      |
| Z13 | CFW.TO       | Calfrac Well Services Ltd           | Energy              | Oil & Gas Equipment & Services | Oil & Gas Equipment & Services | Canada       | North America |
| Z14 | CHK          | Chesapeake Energy Corporation       | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z15 | CIG          | Companhia Energetica de Minas Gerais| Utilities           | Utilities                       | Utilities                       | Brazil      | South America |
| Z16 | CMS          | CMS Energy Corporation              | Utilities           | Utilities                       | Utilities                       | United States | North America |
| Z17 | CNA.L        | Centrica plc                        | Utilities           | Utilities                       | Utilities                       | UK          | Europe    |
| Z18 | CNE.L        | Cairn Energy                        | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z19 | CNQ          | Canadian Natural Resources Ltd      | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z20 | COG          | Cabot Oil & Gas Corporation         | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z21 | COP          | Conocophillips                      | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z22 | COPEC.SN      | Empresas COPEC SA                   | Industrials         | Congo                            | Congo                           | Chile       | South America |
| Z23 | 2883.HK      | China Oilfields Services Limited     | Energy              | Oil & Gas Equipment & Services | Oil & Gas Equipment & Services | China       | Asia      |
| Z24 | CPE          | Callon Petroleum Company             | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z25 | CPL          | CPFFL Energia                       | Utilities           | Utilities                       | Utilities                       | Brazil      | South America |
| Z26 | CVN.AX       | Carnarvon Petroleum Limited         | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | Australia    | Oceania   |
| Z27 | CVX          | Chevron Corporation                 | Energy              | Oil & Gas Integrated           | Oil & Gas Integrated           | United States | North America |
| Z28 | D            | Dominion Energy                     | Utilities           | Utilities                       | Utilities                       | United States | North America |
| Z29 | DCC.L        | DCC PLC                             | Energy              | Oil & Gas Refining & Marketing | Oil & Gas Refining & Marketing | Ireland     | Europe    |
| Z30 | DNO.OL       | DNO ASA                             | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | Norway      | Europe    |
| Z31 | DO           | Diamond Offshore Drilling           | Energy              | Oil & Gas Drilling             | Oil & Gas Drilling             | United States | North America |
| Z32 | DUK          | Duke Energy Corporation             | Utilities           | Utilities                       | Utilities                       | United States | North America |
| Z33 | DYN          | Devon Energy Corporation            | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z34 | E            | Eti S.p.A.                          | Energy              | Oil & Gas Integrated           | Oil & Gas Integrated           | Italy       | Europe    |
| Z35 | EDB.DE       | EnBW Energie Baden-Wurttemberg      | Utilities           | Utilities                       | Utilities                       | Germany     | Europe    |
| Z36 | ECA          | Encana Corporation                  | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | Canada       | North America |
| Z37 | EDF.PA       | Électricité de France               | Utilities           | Utilities                       | Utilities                       | France      | Europe    |
| Z38 | EIX          | Edison International                | Utilities           | Utilities                       | Utilities                       | United States | North America |
| Z39 | ENB          | Enbridge Inc.                       | Energy              | Oil & Gas                       | Oil & Gas                       | Canada       | North America |
| Z40 | ENEL.MI      | Enel SpA                            | Utilities           | Utilities                       | Utilities                       | Italy       | Europe    |
| Z41 | ENG.PA       | ENGIE                               | Utilities           | Utilities                       | Utilities                       | France       | Europe    |
| Z42 | ENG.MC       | Enagas                              | Utilities           | Utilities                       | Utilities                       | Spain       | Europe    |
| Z43 | EOAN.DE      | E.ON SE                             | Utilities           | Utilities                       | Utilities                       | Germany     | Europe    |
| Z44 | EOG          | EOG Resources Inc                   | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z45 | EPD          | Enterprise Products Partners L.P.   | Energy              | Oil & Gas                       | Oil & Gas                       | United States | North America |
| Z46 | EQR          | Equinor ASA                         | Energy              | Oil & Gas Integrated           | Oil & Gas Integrated           | Norway      | Europe    |
| Z47 | EQT          | EQT Corporation                     | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z48 | EXC          | Exelon Corporation                  | Utilities           | Utilities                       | Utilities                       | United States | North America |
| Z49 | 5017.T       | Fuji Oil Company                    | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | Japan       | Asia      |
| Z50 | 6505.TW      | Formosa Petrochemical Corp          | Energy              | Oil & Gas Refining & Marketing | Oil & Gas Refining & Marketing | Taiwan      | Asia      |
| Z51 | 078930.KS    | GS Caltex Corporation               | Industrials         | Conglomerates                   | Conglomerates                   | South Korea | Asia      |
| Z52 | 010950.KS    | S-Oil Corp                          | Energy              | Oil & Gas Refining & Marketing | Oil & Gas Refining & Marketing | South Korea | Asia      |
| Z53 | HAL          | Halliburton Company                 | Energy              | Oil & Gas Equipment & Services | Oil & Gas Equipment & Services | United States | North America |
| Z54 | HES          | Hess Corporation                    | Energy              | Oil & Gas E&P                  | Oil & Gas E&P                  | United States | North America |
| Z55 | HFC          | HollyFrontier Corporation           | Energy              | Oil & Gas Refining & Marketing | Oil & Gas Refining & Marketing | United States | North America |
| Z56 | HINDPETRO.   | Hindustan Petroleum                 | Energy              | Oil & Gas Refining & Marketing | Oil & Gas Refining & Marketing | India       | Asia      |
| Z57 | HP           | Helmerich & Payne                   | Energy              | Oil & Gas Drilling              | Oil & Gas Drilling              | United States | North America |

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### Table 1: (Continued)

| ID   | Stock Ticker | Company Name                      | Sector                  | Industry                                      | Country | Continent |
|------|--------------|-----------------------------------|-------------------------|-----------------------------------------------|---------|-----------|
| Z58  | 600346.SS    | Hengli Petrochemical Co Ltd       | Materials               | Chemical                                       | China   | Asia      |
| Z59  | HSE.TO       | Husky Energy Inc.                 | Energy                  | Oil & Gas Integrated                          | Canada  | North America |
| Z60  | IMO          | Imperial Oil Limited              | Energy                  | Oil & Gas Integrated                          | Canada  | North America |
| Z61  | INT          | World Fuel Services Corporation   | Energy                  | Oil & Gas Refining & Marketing                | United States | North America |
| Z62  | IOC.NS       | Indian Oil Corporation            | Energy                  | Oil & Gas Refining & Marketing                | India   | Asia      |
| Z63  | IRPC.BK      | IRPC Public Company               | Energy                  | Oil & Gas Refining & Marketing                | Thailand | Asia      |
| Z64  | ISRL         | Isramco                           | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z65  | JXX.L        | JKX Oil & Gas                     | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z66  | 5020.T       | JXTG Holdings                     | Energy                  | Oil & Gas Refining & Marketing                | Japan    | Asia      |
| Z67  | KEY.TO       | Keyera Corp.                      | Energy                  | Oil & Gas Midstream                           | United States | North America |
| Z68  | 036460.KS    | Korea Gas Corp                    | Utilities               | Utilities                                     | South Korea | Asia      |
| Z69  | LNG          | Chieniere Energy                  | Energy                  | Oil & Gas Midstream                           | United States | North America |
| Z70  | LUKOY       | PJSC LUKOIL                       | Energy                  | Oil & Gas Integrated                          | Russia   | Europe    |
| Z71  | LUPE.ST      | Lundin Petroleum AB               | Energy                  | Oil & Gas E&P                                 | Sweden   | Europe    |
| Z72  | M05.SI       | MTQ Corporation                   | Energy                  | Oil & Gas Equipment & Services               | Singapore | Asia      |
| Z73  | MARI         | Mari Petroleum Company            | Energy                  | Oil & Gas E&P                                 | Pakistan | Asia      |
| Z74  | MEL.AX       | Metgasco Limited                  | Energy                  | Oil & Gas E&P                                 | Australia | Oceania |
| Z75  | MRO          | Marathon Oil Corporation          | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z76  | MUR          | Murphy Oil Corporation            | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z77  | MXC          | Mexco Energy Corporation          | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z78  | NBL          | Noble Energy                      | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z79  | NBR          | Nabors Industries                 | Energy                  | Oil & Gas Drilling                            | United States | North America |
| Z80  | NDX1.DE      | Nordex SE                         | Industrials             | Diversified Industrials                       | Germany   | Europe    |
| Z81  | NE           | Noble Corporation plc             | Energy                  | Oil & Gas Drilling                            | UK       | Europe    |
| Z82  | NEE          | NextEra Energy                    | Utilities               | Utilities                                     | United States | North America |
| Z83  | NESTE.HE     | Neste Oyj                         | Energy                  | Oil & Gas Refining & Marketing               | Finland   | Europe    |
| Z84  | NGG          | National Grid plc                 | Utilities               | Utilities                                     | United States | North America |
| Z85  | NI           | NiSource Inc.                     | Utilities               | Utilities                                     | United States | North America |
| Z86  | NOV          | National Oilwell Varco            | Energy                  | Oil & Gas Equipment & Services               | United States | North America |
| Z87  | NS           | NuStar Energy L.P.                | Energy                  | Oil & Gas Midstream                           | United States | North America |
| Z88  | NVA.TO       | NuVista Energy Ltd.               | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z89  | OGC          | Oil & Gas Development Company     | Energy                  | Oil & Gas E&P                                 | Pakistan   | Asia      |
| Z90  | OZGZY        | Public Joint Stock Company Gazprom| Energy                  | Oil & Gas Integrated                          | Russia    | Europe    |
| Z91  | OKE          | ONEOK                             | Energy                  | Oil & Gas Midstream                           | United States | North America |
| Z92  | OMV.VI       | OMV Aktiengesellschaft            | Energy                  | Oil & Gas Integrated                          | Austria   | Europe    |
| Z93  | ONGC.NS      | Oil and Natural Gas Corporation   | Energy                  | Oil & Gas Integrated                          | India     | Asia      |
| Z94  | ORG.AX       | Origin Energy Limited             | Energy                  | Oil & Gas Integrated                          | Australia | Oceania |
| Z95  | 9532.T       | Osaka Gas Co Ltd                  | Utilities               | Utilities                                     | Japan     | Asia      |
| Z96  | OXY          | Occidental Petroleum Corporation  | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z97  | PAA          | Plains All American Pipeline      | Energy                  | Oil & Gas Midstream                           | United States | North America |
| Z98  | PBR          | Petroleo Brasileiro S.A. - Petrobras| Energy                  | Oil & Gas Integrated                          | Brazil    | South America |
| Z99  | PDCE         | PDC Energy                        | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z100 | PEY.TO       | Petro Exploration & Development Corp. | Energy                  | Oil & Gas E&P                                 | Canada    | North America |
| Z101 | PFC.L        | Petrofac                          | Basic                   | Oil & Gas Equipment & Services               | Jersey    | Europe    |
| Z102 | PGAS.JK      | PT Perusahaan Gas Negara Tbk      | Utilities               | Utilities                                     | Indonesia | Asia      |
| Z103 | PMO.L        | Premier Oil                       | Energy                  | Oil & Gas E&P                                 | UK       | Europe    |
| Z104 | PNN.L        | Pennon Group                      | Utilities               | Utilities                                     | UK       | Europe    |
| Z105 | PTR          | PetroChina Company Limited        | Energy                  | Oil & Gas Integrated                          | China     | Asia      |
| Z106 | PTT.BK       | PTT Public Company Limited        | Energy                  | Oil & Gas Integrated                          | Thailand  | Asia      |
| Z107 | PXD          | Pioneer Natural Resources Company | Energy                  | Oil & Gas E&P                                 | United States | North America |
| Z108 | RDS-B        | Royal Dutch Shell plc             | Energy                  | Oil & Gas Integrated                          | Netherlands | Europe |
| Z109 | RELIANCE. NS | Reliance Industries               | Energy                  | Oil & Gas Refining & Marketing               | India     | Asia      |
| Z110 | REP.MC       | Repsol                            | Energy                  | Oil & Gas Integrated                          | Spain     | Europe    |
| Z111 | RIG          | Transocean Ltd.                   | Energy                  | Oil & Gas Drilling                            | Switzerland | Europe |
| Z112 | RULPA        | Rubis                             | Utilities               | Utilities                                     | France    | Europe    |
| Z113 | RWE.DE       | RWE Aktiengesellschaft            | Utilities               | Utilities                                     | Germany   | Europe    |
| Z114 | SDRL         | Seadrill Limited                  | Energy                  | Oil & Gas Drilling                            | Bermuda   | North America |
| Z115 | SGRE.MC      | Siemens Gamesa Renewable Energy   | Industrials             | Diversified Industrials                       | Spain     | Europe    |

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Table 1: (Continued)

| ID   | Stock Ticker | Company Name                                      | Sector                | Industry                                    | Country       | Continent |
|------|--------------|--------------------------------------------------|-----------------------|---------------------------------------------|---------------|-----------|
| Z116 | SGTZY        | Surgutneftegas Public Joint Stock Company         | Energy                | Oil & Gas Integrated                        | Russia        | Europe    |
| Z117 | SLB          | Schlumberger Limited                             | Energy                | Oil & Gas Equipment & Services              | United States | North America |
| Z118 | SNP          | China Petroleum & Chemical Corporation/Sinopec    | Energy                | Oil & Gas Integrated                        | China         | Asia      |
| Z119 | SO           | The Southern Company                             | Utilities             | Utilities                                   | United States | North America |
| Z120 | 9908.TW      | Great Taihai Gas Co Ltd                          | Utilities             | Utilities                                   | Taiwan        | Asia      |
| Z121 | SOI.V        | Saturn Oil & Gas Inc.                            | Energy                | Oil & Gas E&P                               | Canada        | North America |
| Z122 | SPM.MI       | Saipem S.p.A.                                     | Energy                | Oil & Gas Equipment & Services              | Italy         | Europe    |
| Z123 | SPWR         | SunPower Corporation                             | Technology            | Solar                                       | United States | North America |
| Z124 | SRE          | Sempri Energy                                     | Utilities             | Utilities                                   | United States | North America |
| Z125 | SRG.MI       | Snam                                             | Utilities             | Utilities                                   | Italy         | Europe    |
| Z126 | SSL          | Sasol Limited                                     | Energy                | Oil & Gas Integrated                        | South Africa  | Africa    |
| Z127 | STO.AX       | Santos Limited                                    | Energy                | Oil & Gas E&P                               | Australia     | Oceania   |
| Z128 | SU           | Suncur Energy                                     | Energy                | Oil & Gas Integrated                        | Canada        | North America |
| Z129 | 600248.SS    | Shaanxi Yanchang Petroleum                        | Energy                | Oil & Gas Integrated                        | China         | Asia      |
| Z130 | TLW.L        | Tullow Oil plc                                    | Energy                | Oil & Gas E&P                               | UK            | Europe    |
| Z131 | TOP.BK       | Thai Oil Public Company Limited                   | Energy                | Oil & Gas Refining & Marketing              | Thailand      | Asia      |
| Z132 | TOT          | TOTAL S.A.                                        | Energy                | Oil & Gas Integrated                        | France        | Europe    |
| Z133 | TRP          | TC Energy Corporation                             | Energy                | Oil & Gas Midstream                        | Canada        | North America |
| Z134 | TS           | Tenaris                                           | Energy                | Oil & Gas Equipment & Services              | Luxembourg    | Europe    |
| Z135 | TUPRS.IS     | Turkije Petrol Rafinerileri                       | Energy                | Oil & Gas Refining & Marketing              | Turkey        | Asia      |
| Z136 | UGP          | Ultraper Participoes                              | Energy                | Oil & Gas Refining & Marketing              | Brazil        | South America |
| Z137 | UKOG.L       | UK Oil & Gas                                      | Energy                | Oil & Gas E&P                               | UK            | Europe    |
| Z138 | VLO          | Valero Energy Corporation                         | Energy                | Oil & Gas Refining & Marketing              | United States | North America |
| Z139 | VWS.CO       | Vestas Wind Systems                               | Industries            | Diversified Industrials                    | Denmark       | Europe    |
| Z140 | WLL          | Whiting Petroleum Corporation                     | Energy                | Oil & Gas E&P                               | United States | North America |
| Z141 | WOPEY        | Woodside Petroleum                                | Energy                | Oil & Gas E&P                               | Australia     | Oceania   |
| Z142 | WOR.AX       | WorleyParsons Limited                             | Energy                | Oil & Gas Equipment & Services              | Australia     | Oceania   |
| Z143 | XEC          | Cimarex Energy Co.                                | Energy                | Oil & Gas E&P                               | United States | North America |
| Z144 | XOM          | Exxon Mobil Corporation                           | Energy                | Oil & Gas Integrated                        | United States | North America |
| Z145 | 600188.SS    | Yanzhou Coal Mining Co Ltd                        | Basic                 | Coal                                        | China         | Asia      |
| Z146 | YPF          | Sociedad Anónima                                  | Energy                | Oil & Gas Integrated                        | Argentina     | South America |
| Z147 | YUMA         | Yuma Energy                                       | Energy                | Oil & Gas E&P                               | United States | North America |

The influence strength (IS) of a particular node is the summation of the associations or correlations of the node with all other connected nodes (Kim et al., 2002), it is calculated as:

\[ S_i = \sum_{j \in I_i} \rho_{ij} \]  

(6)

Where \( \rho_{ij} \) is Pearson correlation coefficient between two stocks \( i \) and \( j \), and \( I_i \) signifies set of nodes directly connected to node \( i \). To examine the shortest distance from a node to other nodes in the MST networks, we use closeness centrality measure that is applied to observe the power associated with the node (Tabak et al., 2010). Given a node \( i \) in a network containing \( N \) nodes, it is calculated as follows:

\[ C(i) = \frac{1}{d_i} = \frac{N - 1}{\sum_{j=1}^{N} d_{ij}} \]  

(7)

Where \( d_{ij} \) is the distance between two stocks \( i \) and \( j \). Further, to analyze the mediator roles of energy stocks in the MST network, we apply betweenness centrality measure. For a node \( i \) the betweenness centrality is given as (Freeman, 1977):

\[ B(i) = \frac{1}{\sum_{k=1}^{N} \frac{\sigma_{kh}}{\sigma_{kh}}(i)} \]  

(8)

Where \( \sigma_{kh}(i) \) represents shortest routes among nodes \( k \) and \( h \) that pass-through node \( i \), and \( \sigma_{kh} \) characterizes total number of shortest paths among \( k \) and \( h \).

To examine dynamic properties of the MST network, we divide our sample period 2006-2019 into \( T \) windows \( t = 1, 2, \ldots, T \), having a width \( L \) to approximately 1 year. Furthermore, normalized tree length (NTL) and average path length (APL) is used to assess the time-varying length of MST networks. The formula for calculating NTL denoted as \( L(t) \) is as follows (Yao and Memon, 2019):

\[ L(t) = \frac{1}{N(N-1)} \sum_{(i,j) \in T} d_{ij} \]  

(9)

The average path length (APL) is described as the mean distance among two stocks in a network, as follows:

\[ L(t) = \frac{1}{2} \frac{1}{N(N-1)} \sum_{i \neq j} d_{ij} \]  

(10)
4. RESULTS

4.1. Statistical Analysis

Table 2 mentions summary of correlation matrices that have been obtained by splitting our data into different $T$ windows of length $L$, and the overall sample period. We immediately observe highest correlation of 0.341, and standard deviation of $\sigma=0.243$ among energy stocks during the year 2008, the time when global financial crisis struck stock markets of the world. An increase in the average correlation of 0.332 is also encountered in the year 2011, during energy and European debt crisis period. Further, Figure 1 presents time varying history of oil and gas prices from 2006 to 2019, in-line with the sample period of our study. Since, oil price is considered a core determinant of economic growth (Dagher and El Hariri, 2013), and higher oil prices leads to economic recessions (Hamilton, 1983; Pönkä and Zheng, 2019). Therefore, it is crucial to observe the state and network structures of world energy companies during the time periods of 2008 and 2011, respectively. From Figure 1, we instantly observe a spike in the oil price during crisis time period of 2008. The Arab spring and ambiguity over Libyan oil output spread fears in the energy markets specifically resulted in sharp increase in the crude oil prices, causing 2011 energy crisis. The high average cross correlations among the energy stocks of the world represents strong interaction among stocks during crisis time. Additionally, the average cross correlation during entire sample period from 2006 to 2019 for the world energy companies remain at 0.240. Moreover, higher positive skewness of 1.214 is observed during the year 2017, possibly reflecting strong interaction among energy companies of the world.

4.2. Correlation Threshold Networks in the World Energy Companies

Given a network of 147 energy stocks of the world, and 147 (147−1)/2 total number of edges in the correlation matrix, we define threshold $\theta$ a value, such as: ($−1 \leq \theta \leq 1$) to chop the edges. For different correlation thresholds $\theta$, any edges whose correlations are higher than the threshold are filtered. Therefore, we obtain high amount of edges at lower $\theta$ levels. Based on our correlation matrices, we examine energy companies’ threshold network through edge filtering procedure with a step of 0.1. Figure 2 presents amount and percentage of retaining edges during various interval levels of thresholds for the two subsample periods 2008 and 2011, and overall sample period. We can see the amount and percentage of retaining edges of the threshold network declines, with an increase in the threshold level. Additionally, we observe higher number of edges in the threshold network for energy companies during subsample periods, in comparison with the overall sample period, verifying our previous findings of high correlations during crisis period.

Figure 3 presents three different networks at $\theta > 0.3$ of 2008, 2011, and overall sample periods. All nodes are sized based on their degree of centrality, and colored by its geographical distribution of continent of the company. We observe dense networks at correlation threshold level of 0.3, where two thresholds networks of 2008, and 2011 are calculated to be extreme denser in comparison with the network of
overall sample period. By highlighting top stocks of the threshold network, we can easily observe details of the overall networks. The top stocks\(^4\) with largest values of the degree of connections at \(\theta > 0.3\) during 2008 are: \(Z_{40}\) (Enel S.p.A. 115), \(Z_{139}\) (Vetas wind systems 115), and \(Z_{115}\) (Siemens Gamesa renewable energy 114). We observed that all of the top nodes belong to European continent that carry important role in the network. Comparing it with 2011 network at \(\theta > 0.3\), the Italian top energy company holds principle position in the network, out of four companies in total, and these are: \(Z_{122}\) (Saipem S.P.A. 118), \(Z_{12}\) (CNOOC 113), \(Z_{101}\) (Petrofac 113), and \(Z_{128}\) (Suncor energy 113). However, the degree of connections of important nodes of the overall sample network at \(\theta > 0.3\) is much lower. These key nodes are calculated to be Italian based company \(Z_{34}\) (Eni S.p.A. 99), and France based company \(Z_{132}\) (Total S.A. 97).

Figure 4 shows three different networks at a higher \(\theta > 0.7\) of 2008, 2011, and overall sample periods. All nodes are sized based on betweenness centrality, and colored by its geographical distribution of the continent of the company. Immediately, we observe the break of whole network into small components, along with the subsequent decline in the network density at a higher threshold level. In terms of degree of connectivity, two top most important stocks are US based, namely: \(Z_{27}\) (Chevron Corporation) connecting directly with 53 and 46 companies during crisis time of 2008 and 2011, and \(Z_{21}\) (ConocoPhillips 23) for the overall sample period. Therefore, the influence of US based energy companies is visible during crisis periods and overall sample period at higher threshold level of 0.7. Additionally, the stocks during crisis periods of 2008 and 2011 are clustered together, behaving like a herd or flock. With regard to betweenness centrality, the stocks\(^5\) that represents highest short routes are: \(Z_{98}\) (Petrobras 152.111) during the year 2008, \(Z_{34}\) (Eni S.p.A. 468.141) during the year 2011, and \(Z_{81}\) (Noble Plc 62.729) during overall sample period.

Moreover, Table 3 presents topology of correlation threshold networks at different intervals with bins of 0.1. We also built

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\(^4\) The number besides company name represents degree of connections of the company.

\(^5\) The number besides company name indicates betweenness centrality score of the company.
networks and explore the topology of negative values of correlation threshold at $\theta > 0$, that shows high number of nodes and increased density for crisis periods of 2008 and 2011 among world energy companies. Additionally, we observe high modularity of 0.688,
and 0.667 at top most threshold level of $\theta > 9$ for the crisis periods of 2008 and 2011, and 0.86 at higher threshold $\theta > 8$ for overall sample period, respectively. This implies strong bond among stocks while containing communities within a threshold network. Similarly, few recent studies have reported high modularity among stocks during crisis time (Memon and Yao, 2019; Lee and Nobi, 2018).

4.3. Minimum Spanning Tree (MST)

In this section, we present three MSTs of 147 energy companies of the world, based on the separation of our data into two subsamples for crisis periods of 2008, and 2011, while comparing it with overall data sample network to examine network evolving connectivity and influence of stocks. In the MSTs, all nodes are colored based on their geographical distribution of continents.

The overall energy stock market network across the whole period of study is presented in Figure 5. We immediately observe substantial clustering based on geographic positioning of energy companies. The results show three prominent clusters: the north American energy companies (red) in the left, the European energy companies (green) in the bottom right, and the Asian energy companies (blue) in the top right. Several studies have reported homogenous clustering in the MST networks of stock markets (Majapa and Gossel, 2016; Yao and Memon, 2019; Coletti and Murgia, 2016). In addition, Table 4 presents top energy stocks based on their degree of connections. The Asian energy giant, the China oilfield services company ($Z_{23}$) holds central or hub position in the overall MST with 8 degree of connections. Other key nodes in the MST network with six degree of connections include 2 US, 1 Australian, and 4 European energy companies. The acquisition of central or key positions in the overall MST network is not unusual, given the fact that it has been acquired by top energy companies of the world. Moreover, the results show high average degree of connection for European energy companies of 2.15, followed by Asian energy companies score of 1.965, and north American energy companies score of 1.938 in the overall MST network. This represents high influence and importance of European energy companies in the overall MST network.

**Table 4: List of the top stocks with the highest degree of connections in MST of World energy stocks.** As is shown, the top energy stocks are diverse in the country of origin which includes 1 China stock, 2 US stocks, 1 Italy stock, 1 Norway stock, 1 Spain stock, 1 Australia stock and 1 UK stock.

| Degree | Node ID | Company Name                  | Industry          | Country       |
|--------|---------|-------------------------------|-------------------|---------------|
| 8      | Z23     | China Oilfield Services Ltd.  | Oil & Gas Equipment & Services | China         |
| 6      | Z2      | American Electric Power Co.   | Oil & Gas Integrated | United States |
| 6      | Z33     | Devon Energy Corp.            | Oil & Gas E&P     | United States |
| 6      | Z40     | Enel SpA                       | Oil & Gas Integrated | Italy         |
| 6      | Z46     | Equinor ASA                   | Oil & Gas Integrated | Norway        |
| 6      | Z110    | Repsol                        | Oil & Gas Integrated | Spain         |
| 6      | Z127    | Santos Limited                | Oil & Gas E&P     | Australia     |
| 6      | Z130    | Tullow Oil plc                | Oil & Gas E&P     | UK            |

Figure 5: MST of 147 world energy companies during entire period of study from January 2006 to June 2019. Color coding: Asian companies in blue, South American companies in cyan, European companies in green, African companies in grey, North American companies in red, and Oceania in yellow.
Additionally, the European energy companies also dominate with high average betweenness centrality score of 665.325, followed by North American companies betweenness score of 558.554, representing strong intermediary role by European and North American energy companies in the overall MST network.

The crisis period MST 2008 of 147 world energy companies is presented in Figure 6, and shows different structure of MST, where Asian energy companies (blue) are detached and connected with companies from three different continents. However, energy companies belonging to Europe or North American region are still intact and clustered together. In addition, Table 5 shows appearance of two hub nodes of US based Occidental petroleum (Z_{96}), and German based utilities company E.ON SE (Z_{43}), connecting directly with 10 and 8 nodes in the MST. Additionally, MST structure during the period of global financial crisis 2008 comprises, 49.66% of nodes’ (i.e. 73 stocks) degrees are equal to one, around 25% (37 stocks) of nodes’ degrees equal to two, almost 15% (22 stocks) of nodes’ degrees equal to three, 4% (6 stocks) of nodes’ degrees equal to four, and 4.76% (7 stocks) of nodes’ carry degrees of five and six. The companies with number of links >6 is around 1.36% from the total number of vertices in the network.

Similar to the MST structure of 2008, Figure 7 shows broken cluster and sparse Asian energy companies in MST map. Additionally, we observe split of European energy companies that has been detached and connected with North American companies in two groups. Therefore, there is only 1 dominant cluster of North American companies (red) in the MST map of 2011. Moreover, Table 6 presents two star-like hub nodes of US based Apache corp. (Z_4), and Italian based Saipem S.p.A. (Z_{122}), directly connecting with 11 and 10 nodes in the MST network. While comparing the

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**Table 5: List of the top stocks with highest degree of connections in the MST of World energy stocks over the year 2008.** As is shown, Occidental Petroleum stock from US is the most connected stock in the MST with a degree of 10. The rest of stocks having degree >5 are composed of 1 Germany stock, 1 UK stock, and 1 US stock

| Degree | Node ID | Company Name                  | Industry                  | Country |
|--------|---------|--------------------------------|---------------------------|---------|
| 10     | Z96     | Occidental Petroleum Corporation | Oil & Gas E&P             | United States |
| 8      | Z43     | E.ON SE                        | Utilities                 | Germany |
| 6      | Z18     | Cairn Energy                   | Oil & Gas E&P             | UK      |
| 6      | Z33     | Devon Energy Corporation       | Oil & Gas E&P             | United States |

**Table 6: List of the top stocks with highest degree of connections in the MST of World energy stocks over the year 2011.** As is shown, Apache stock from US is the most connected stock in the MST with a degree of 11. The rest of stocks having degree >5 are composed of 2 Italy stocks, 2 US stocks, 1 Canada stock, and 1 Australia stock

| Degree | Node ID | Company Name                  | Industry                  | Country |
|--------|---------|--------------------------------|---------------------------|---------|
| 11     | Z4      | Apache Corp                    | Oil & Gas E&P             | United States |
| 10     | Z122    | Saipem S.p.A.                  | Oil & Gas Equipment & Services | Italy |
| 7      | Z40     | Enel SpA                       | Utilities                 | Italy |
| 7      | Z124    | Sempra Energy                  | Utilities                 | United States |
| 7      | Z128    | Suncor Energy                  | Oil & Gas Integrated      | Canada |
| 6      | Z33     | Devon Energy Corporation       | Oil & Gas E&P             | United States |
| 6      | Z127    | Santos Limited                 | Oil & Gas E&P             | Australia |

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**Figure 6:** MST of 147 world energy companies during global recession Year of 2008
two crisis period MSTs, companies with number of connections >6 is about 3.40% (5 stocks) for 2011, and 1.36% (2 stocks) for 2008 from total number of vertices in the network. To sum up, the crisis period structures confirm formation of low clusters, sparse nodes, and appearance of star-like hub nodes in the MST map.

4.4. Centrality Structures of Minimum Spanning Trees
We apply centrality measures on three MSTs to examine dominance of energy companies of the world. After calculating three prominent centrality tests of each and every node, Table 7 ranks top five nodes based on their individual score. Considering overall MST, three top US energy companies namely: Devon energy ($Z_{33}$), American electric power ($Z_{2}$), and Occidental Petroleum ($Z_{96}$) appear to be most influential stocks in the network, followed by European top energy companies. Despite having lower degree of connections of six, in comparison with eight degree of connections of Asian based China Oilfield Services ($Z_{23}$) in the overall MST network, these companies have more power to influence the entire MST network. The betweenness and closeness centrality test nominate France based Total S.A. ($Z_{132}$) energy company taking intermediary or bridge role in the overall MST network. During crisis periods of 2008 and 2011, US top energy companies namely: Occidental petroleum ($Z_{96}$), Apache Corporation ($Z_{4}$), along with France based Total S.A. ($Z_{132}$) appears on the top position among all stocks in the MSTs. Finally, the centrality structures of MSTs reveal few top US and European based companies occupying important and great global influence positions in the MST networks. Therefore, the rise and fall of these few nodes will impact the stability structure of entire energy companies’ network. In addition, there is always a chance of rapid spread of systematic risk towards the entire network structure of world energy companies, as external shock can transmit easily and quickly.

4.5. Dynamic Structure of Energy Stocks Networks
The distance $d_{ij}$ specifies the correlation among stocks, i.e. the higher the distance the smaller the correlation among two stocks and vice versa. Figure 8 presents dynamic mean distance $\langle d_{ij} \rangle$, and total distance $d_{total} = \sum_{i,j} d_{ij}$ of the overall distance matrix, and MST, by taking into account varied edge numbers. It can be calculated as follows:

$$\langle d_{ij} \rangle = \frac{1}{N(N-1)/2} \sum_{i,j} d_{ij}$$  \hspace{1cm} (11)

$$\langle d_{ij} \rangle = \frac{1}{N-1} \sum_{i,j} d_{ij}$$  \hspace{1cm} (12)

Our results suggest similar pattern of four figures, which means MST presents a backbone of the original network, and the parallel trend stays robust over time. Similarly, the distances present a sharp decline during crisis periods of 2008 and 2011, hinting towards tight correlations among energy stocks. But soon after crisis period of 2011, a gradual increase and stability among energy market is also observed.

Figure 9 shows dynamic results of NTL and average path length in the minimum spanning tree network of length $T=14$. The dynamic APL represents fluctuation pattern and information escalation for the world energy stocks. Additionally, the NTL curve shows
Table 7: For the world energy stocks network, we present top five stocks based on centrality measures of influence strength ($S_i$), betweenness centrality ($B_i$), and closeness centrality ($C_i$), for 2008, 2011, and overall study period.

| Rank | Node ID | Company                  | Influence Strength | Betweenness Centrality | Closeness Centrality |
|------|---------|--------------------------|--------------------|------------------------|----------------------|
| 1    | Z33     | Devon Energy             | 4.492              | Z132 TOTAL S.A.        | 0.204                |
| 2    | Z2      | American Electric Power  | 4.358              | Z27 Chevron Corporation| 0.199                |
| 3    | Z132    | Total S.A.               | 3.946              | Z46 Equinor ASA        | 0.189                |
| 4    | Z96     | Occidental Petroleum     | 3.693              | Z12 CNOOC Limited      | 0.182                |
| 5    | Z46     | Equinor ASA              | 3.599              | Z126 Sasol Limited     | 0.177                |

Figure 8: Dynamic evolution of mean and total distances of overall network, and MST for world energy stocks over time in the study period. We used time windows and length of $T=14$

Figure 9: Dynamic evolution of normalized tree length (NTL), and average path length (APL) of MST. We used time windows and length of $T=14$

Extreme network contraction during time periods of global recession 2008, and oil price hikes coupled with European debt crisis of 2011 for the world energy stocks. Additionally, the results show a valley, possibly due to high correlation among stocks during crisis periods. Previous studies in literature point towards correlation move to one during crisis, which is a sign of instability for the stock markets (Yao and Memon, 2019; Papenbrock and Schwendner, 2015). We also observed high expansion of the MST network for the year 2017, which was robust year for stocks and energy market. The global energy market exceeded $1.4$ trillion during the year 2016, representing a massive increase of 7%.
compared to earlier year. Simultaneously, a constant expansion after crisis periods of global recession 2008, oil price shocks, and European debt crisis is being observed showing economic recovery after crisis periods.

5. CONCLUSION

In this paper, we investigated network structures and dynamics of popular 147 energy stocks from 34 countries through properties and models of complex network theory. We used data spreaded approximately 14 years, from January 03, 2006 to June 28, 2019. Additionally, this study compares network structures of two sub-sample periods including: Global financial crisis 2008, energy and European debt crisis period of 2011, and overall sample period. We present time varying statistical analysis of correlation coefficients, correlation threshold networks, the clustering structure of MSTs, the centrality measures of MSTs, and importance of nodes and identification. We also examine time evolving distance matrices, and dynamic topological properties of MSTs.

Our results show strong correlations and interaction among energy companies of the world during crisis periods of 2008 and 2011. From the correlation threshold network, we examined a decline in the amount and percentage of retaining edges with an increase in the threshold level. Additionally, we observed higher influence and stability of US based energy companies during crisis periods. For the MST networks, we found three prominent clusters belonging to North American, European, and Asian energy companies in the overall MST map. During crisis periods, only one cluster of North American companies remains intact, and rest of the two clusters are detached. The Asian energy giant China oilfield service appear to be hub node in the overall MST. However, the importance and influence of European and North American energy companies is highly visible in the overall MST network. During sub-sample crisis periods, we observed star-like hub nodes of Occidental petroleum, E.ON SE for 2008, and Apache Corporation, and Saipem S.P.A. for 2011. The centrality measurement results stated the influence of few top US and European energy companies in MSTs. In addition, there is always a chance of rapid spread of systematic risk towards entire energy companies’ structure. Moreover, time varying topological measures highlighted substantial decline in the tree length during crisis time periods and economic recovery after crisis period.

We have built energy companies network structures based on correlation coefficients. Perhaps, our future work will explore additional methods of constructing energy companies network such as: partial correlation method (Wang et al., 2018), and tail dependence networks (Wen et al., 2019). In addition, the results and implications of our study will provide guidance for a wide audience including: individual investors, multinational organization, policy makers and government agencies.

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### APPENDIX A

Table A1: Websites for well-known energy companies of the world

| S. No | Website                                                                 |
|-------|-------------------------------------------------------------------------|
| 1     | https://top250.platts.com/Top250Rankings                                |
| 2     | https://www.thomsonreuters.com/en/products-services/energy/top-100.html  |
| 3     | https://www.worldatlas.com/articles/biggest-oil-companies-in-the-world.html |
| 4     | https://en.wikipedia.org/wiki/List_of_largest_oil_and_gas_companies_by_revenue |
| 5     | https://www.value.today/world-top-companies/energy                       |
| 6     | https://www.offshore-technology.com/features/largest-oil-and-gas-companies-in-2018/ |
| 7     | https://www.investopedia.com/articles/investing/022516/worlds-top-10-utility-companies.asp |
| 8     | https://www.power-technology.com/features/top-10-power-companies-in-the-world/ |