A Complex Network Analysis of the OPEC Crude Oil Trade Network

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***Abstract*—Quantification and analysis of global oil trade networks reveals deep insights into a nation's development and influence at a global scale. Further, it allows us to predict future trends and changes to adapt state policy as the crude oil market influences the balance of power among the developed and emerging economies alike as it is central for energy needs as well for industrial progress. In this paper we analyzed the crude oil export data from 2016 to 2022 from Organization of Petroleum Exporting Countries and their allies (OPEC+) using complex networks in order to quantify and create a comparison metric between the exporting and importing nations to identify changes in the trade network. Our analysis revealed that that subsequent to the COVID-19 pandemic, even after sizable economic recovery, Organization of Petroleum Exporting Countries (OPEC) is unable to maintain pre-pandemic levels of trade due to multiple factors such as the rise of the USA as the leading oil exporter [14] [15], global financial sanctions on Russian federation resulting in influx of discounted oil in the markets [16], shift of world towards renewable energy [17] etc.**

As entering 2022 with the recovery of global oil trade the increase was 8.09% as compared to the loss of 12.35% on the onset of 2020. Our study also opens up possible research work in this direction about other major non-OPEC oil exporters and quantify how their control is increasing over the market.

***Index Terms*—Complex Networks, OPEC, Crude Oil trade**

I. Introduction

Crude oil trade, the backbone of emerging and developed economies, is one of the most vital resource for security and stability of a nation. For the control and security of this "Black Gold". As there exists an ever-increasing demand for energy in the world, we analyze the effect of world events on the crude oil supply chain and study the change in export relationships of the individual nations over a recent period of time.

Currently, the world's top producers of the crude oil are a part of the Organization of Petroleum Exporting Countries and their allies (OPEC+) and they regulate their oil production capacity according to the quotas given to them. As of October 2023, the production from OPEC+ nations led by Saudi Arabia has led to a very large cut which began in 2022 [18]. This cut has led USA to release more of its strategic oil reserves [19] and increase its own production to be sold in the global markets and become the biggest oil exporting nation in the world, thereby, slowly expecting to make crude oil as their major export item in the world market in 2023.

The world's events greatly affect the oil prices and the global crude oil market. For example, Venezuela, despite having the world's largest reserves of crude oil, is barely exporting on par of its capabilities due to the sanctions imposed by the United States government attributing terrorism, drug trafficking-related sanctions among other things [20]. Similar is the case with countries such as Iran which is under heavy US sanctions post the toppling of US-allied Shah of Iran during the revolution alienating the supply of Iranian oil from the world market [21].

A. Related Work

In Zhou et al., 2022 [1], analyzed the trade competition networks and potential competing links and showed how the import competition is shifted away from Europe and America to Asia-Pacific region, mostly between the two large nations India and China. Also their work showed how the rise of new exporting nations have affected the export market and OPEC's control over the global oil prices. They concluded with the observations of the effects of excessive impact of US and it's allies over the control and restructuring of the global oil trade pattern and identifying the oil export competition evolution is heavily influenced by geopolitics.

In Al Rousan et al., 2018 [2], focused on the dynamic network analysis of OPEC And Non OPEC members and found that the level of cooperation between major oil-producing countries changed over time. They quantified the strength of individual nations using novel technique where they define it by measuring the change of other nations oil production with respect to it. They also proved that the decisions of OPEC affected the crude oil export of non-OPEC nations as well and also show the coordination between OPEC nations decreases substantially after 2012 where as non-OPEC nations show no such pattern.

In Ramcharran, 2002 [3], built further on analysis of Griffin's model [13] to identify the results contrasting to it as support of the competitive hypothesis; Instead, a negative and significant price elasticity of supply is obtained which partially supports the target revenue theory showing the loss market share and drop in oil based economies paving a way in the changes of the global market and shift to other exporters, And further expand on the future challenges faced by OPEC.

In Loderer, 1985 [4], established a definite relationship between OPEC cartel formation and curtailment of spot oil prices during the period 1974-1983. Author was able to find direct correlation of OPEC policies on oil price during (1981-1983) and for the period (1974-1980) there were no significant relationship between them, showing OPEC as cartel is effective but only to some extend further more the argument of OPEC as a trade association (without colluding) are ameliorated by the positive correlation in the oil prices.

In Du et al., 2017 [5], investigated the most important nations in the global crude oil trade network from 2002 to 2013. They employed a custom closed-system input-output method in tandem with top network analysis method while taking direct and indirect effects in account and have found the important exporting nations such as Russia, Saudi Arabia, United Arab Emirates,etc. and importing nations such as China, United States of America, India and Japan, etc. Further this research shows that these nations are the one with greater influence and are also with a larger oil trading volume and even major importing counties have influence over major exporting countries not just minor exporters.

In Fattouh & Mahadeva, 2013 [6], conducted an evolution study of OPEC by using multiple models on key events in the oil market in order to quantify OPEC's pricing power. They showed it is effective in short terms and is not sustainable for long duration's. The OPEC's lack of effectiveness in long-term is contributed by several factors like taxation, climate change and energy security policies. The research also highlights 50 years of OPEC history and how it evolved with the market to keep prices in a profitable range for it member nations.

II. Methodology and Data-set

Here we present the dataset created, methodology followed, and metrics used for our complex network analysis of global oil trade network. The created dataset is published through IEEE Dataport [12] https://dx.doi.org/10.21227/m8ds-nd06.

A. Data-set Creation

We collected and processed the necessary data from various sources including the OPEC official website [7], Macrotrends website [8], and Statista [9]. The data from OPEC official website [7] is allowed for academic purposes. The data-set selected is the OPEC Member's crude oil exports by destination in 1,000 barrels per day (b/d) from 2016 to 2022. Further, the average crude oil prices adjusted for inflation is collected from Macrotrends website [8]. Finally, the global demand of oil in million barrels per day (mb/d) sourced from Statista [9] for the fiscal year.

B. Methodology

For the analysis, we modeled the data as a weighed directed graph with OPEC nations and importing regions as nodes of the graph and export volume from the OPEC nations as the weights of the edges. We analyzed the dataset using Gephi [11] and plotted the results using Yifan Hu Proportional model. The following parameters were calculated from the graph: the average nodal degree, average weighted nodal degree, graph density, modularity, and the tatistical inference are used to quantify and compare the data over different years. Total 6 graphs are made for each year from 2016 to 2022.

The 11 OPEC exporting nations of Saudi Arabia, Venezuela, Algeria, Angola, Congo, Kuwait, Guinea, Gabon, IR Iran, Iraq, Libya, Nigeria, United Arab Emirates are added as exporting nodes in the network graph. In addition, 13 importing regions of India, China, The Organization for Economic Co-operation and Development (OECD) Americas, OECD Asia Pacific, OECD Europe, Other Asia, Latin America, Middle East, Africa, Russia, Other Eurasia, Other Europe are added as the importing nodes in the networking graph. Thus the total number of nodes in the network is 25 and we analyzed their import and export relationship using the weighted edges where weights the volume of crude oil in 1000 b/d.

C. Metrics

For the quantification we are employing the following complex network metrics or the domain specific metrics: (i) Average Degree, (ii) Average Weighted Degree, (iii) Graph Density, (iv) Modularity Mod, (v) Statistical Inference, and (vi) Average Closing Price.

1) Average Degree: Average Degree (AD) is a node-level metric for a complex network which can be estimated by taking the ratio between number of edges (E) of a node and number of nodes/vertices (V). It can be obtained for a network as the sum of the degrees of the vertices divided by the number of nodes in the network. AD can be obtained by the following equation for a network:

$$AD = \frac{1}{V} \sum_{i=1}^{V} k_i \tag{1}$$

where k_i is the neighbor degree of the i^{th} node in the network.

2) Average Weighted Degree: Average Weighted Degree (AWD) is obtained from average degree with the the edge weights (W) are also considered as follows:

$$AWD = \frac{WE}{V} \tag{2}$$

3) Graph Density: Graph Density (GD) is a ratio between the number edges present to the maximum number of edges possible in the network. It can be estimated as follows:

$$GD = \frac{|E|}{|V|(|V|-1)} \tag{3}$$

4) Modularity: Modularity (Mod) is the measure of dense internal connection it is given by the following equation

$$Mod = \frac{1}{2e} \sum_{ij} \left(D_{ij} - \gamma \frac{k_i k_j}{2e} \right) \delta(h_i, h_j) \tag{4}$$

where e is the number of edges (or sum of all edge weights),D is the adjacency matrix of the network, k_i is the (weighted) degree of i, γ is the resolution parameter, and $\delta(h_i, h_j)$ is 1 if i and j are in the same community else 0

5) Statistical Inference: Statistical Inference (SI) is an approach for estimating the assortative communities in the network. An assortative community in a network refers to a pattern of connections where nodes tend to link to other nodes that are similar in some way. This concept is often used in the context of social networks, trade networks, and many other networks including technological networks. Assortativity can be based on various node attributes, such as degree (number of connections), age, language, location, or any other relevant characteristic.

In assortative mixing or assortative networking, nodes preferentially attach to others that are similar interms of metrics such as based on degree or other attributes. Degree-based assortativity is one of the most commonly studied forms, where nodes with a similar number of connections (degree) are more likely to connect to each other. For example, in a trade network, organizations with many connections are more likely to be connected with other similar organizations. Another approach is attribute-based assortativity where the nodes that share certain attributes or characteristics are more likely to form connections.

As described in [10] we use their non-parametric Bayesian formulation to deduce the assortative communities in the graph.

6) Average closing price of crude oil: Average closing price of crude oil (ACP) is a metric specific to the Oil trade network that we considered. It is the average of closing price in United States Dollar (USD) per barrel of oil at the end of trading day. It can be used for estimating the price changes in a conclusive manner.

III. Network Analysis Results & Observations

We analyzed the crude oil trade network dataset created from multiple sources using the metrics described in the above section. We present the seven crude oil network graphs for the fiscal years in this section. All the graphs follow similar definition where the nations are represented as nodes and the edges denote the volume of crude oil trade. The width of the edge nodes mark the magnitude, in proportion, of the volume. The networks depicted in the figures of this section are directed graphs where the edges start from exporting nations nodes (shown by Pink colored circles) to the importing nation nodes (shown by Green colored circles). All the nodes are labeled and the edge weights are also displayed on the edges.

Figure 1 shows the crude oil trade network of the year 2016 which showed a low overall trade volume. This low trade volume was contributed primarily due to the increase in the shale oil production by the USA, receding geopolitical concerns, and shifting OPEC policies.

Compared to the oil trade network, our analysis of the network for the year 2017 demonstrated a completely different scenario where a global oil price rise was observed. This oil price rise was mainly due to the curtailments by the OPEC and high demand for crude oil as can be observed from Figure 2.

However, in 2018, the geo-political issues created a different trade network as can be observed in Figure 3. Not only the factors for the year 2017 continued to 2018, but also an increased US sanctions on Iran curbed up Iran's petroleum exports. Similar increase to the other bigger exporters increased the production to manage the global demand.

Figure 4 shows the oil trade network for the year 2019. This year was plagued with OPEC output cuts and geopolitical supply disruptions. However, the growth in US shale oil production kept the market in check.

The year 2020 was a completely different year for the world's trade networks, irrespective of the categories. The spread of Covid-19 pandemic caused the global trade networks to be disrupted causing the oil demand to fall and as a result, the exports of crude oil fell to lowest level as can be seen from Figure 5. However, in 2021, a recovery of oil trade was visible (see Figure 6). Post Covid19 pandemic, the world became a different place with an increase in the renewable energy focus. While the crude oil market saw an increase in the global crude oil demand and prices after the second wave of Covid-19 pandemic. However, due to the global geopolitical events [29] and shift of countries towards sustainable growth models caused the exports remained nominal as can be seen from Figure 6.

The crude oil trade network for the year 2022 showed very high demand which were mainly driven by the geopolitical instability. The prices have reached a record high due to an OPEC output cut. However, the ongoing conflict in Ukraine has allowed the trade of inexpensive Russian oil to be available to selected nations in the region due to the trade embargo placed on Russia. This resulted in lowering the price of crude in the region as can be seen from Figure 7.

A. Performance of Metrics of the Crude Oil Network

Table I shows the behavior of the complex network metrics such as AD, AWD, GD, Mod, SI, and ACP. From the table, we can observe how global events have caused changes in the crude oil trade. For example, the lowest Mod in 2020 showed the effect of global Covid-19 pandemic and loss in demand worldwide. Further more in 2022, the ACP gone highest due to the recent cuts in crude oil production after observing GD we can see how the global geopolitical situation has caused it fall down sharply to denote loss of trade between nodes if compared to previous fiscal years i.e. the links are clustering to dominant nodes or suppliers this is further supported by the value of AD in 2022 reaching the lowest it has been for the period in question.

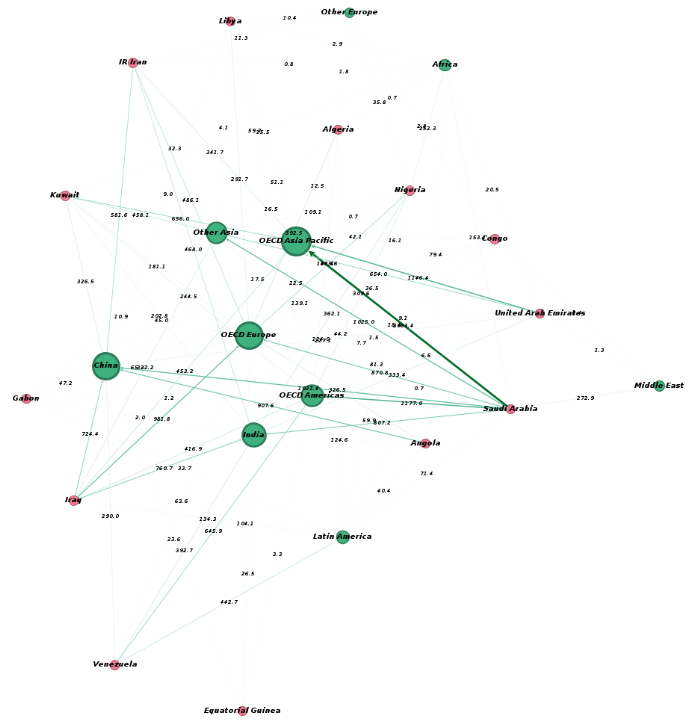

Fig. 1. Crude oil trade network of the year 2016, depicting a low overall trade volume. The low trade volume was contributed primarily due to the increase in the shale oil production by the USA, receding geopolitical concerns, and shifting OPEC policies [22].

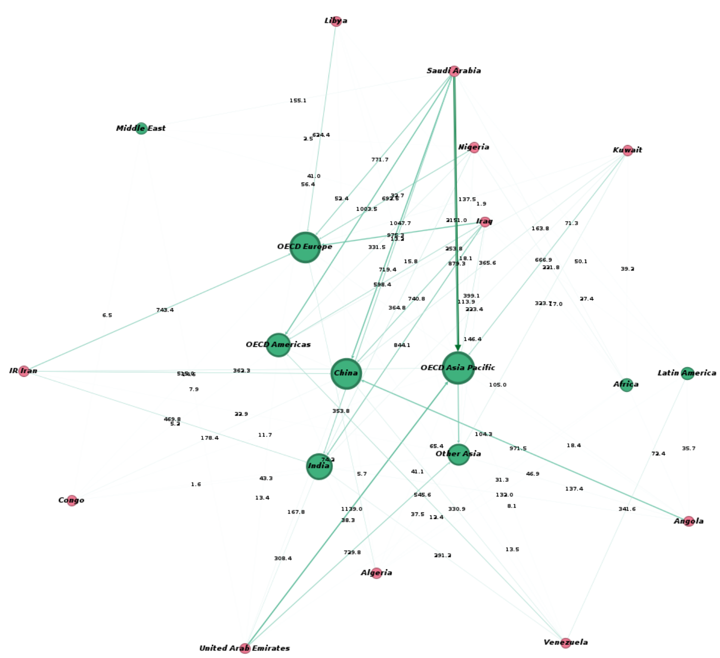

Fig. 2. Crude oil trade graph network of the year 2017. The global oil price rzise can be observed here due the curtailments by the OPEC and high demand for crude oil [23]. Increase in price and export quantity were observed in 2017.

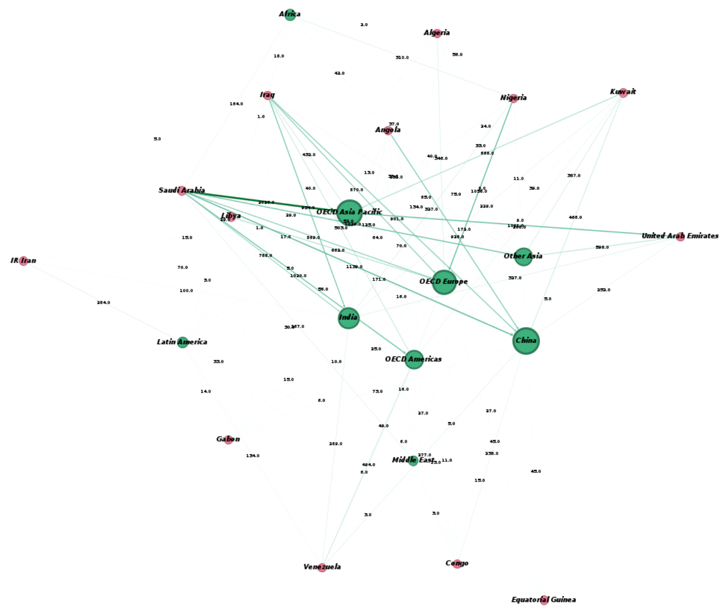

Fig. 3. 2018's crude oil trade network. Previously mentioned factors for the year 2017 and the increased US sanctions curbed up Iran's petroleum exports [24]. Similar increase to the other bigger exporters increased the production to manage the global demand.

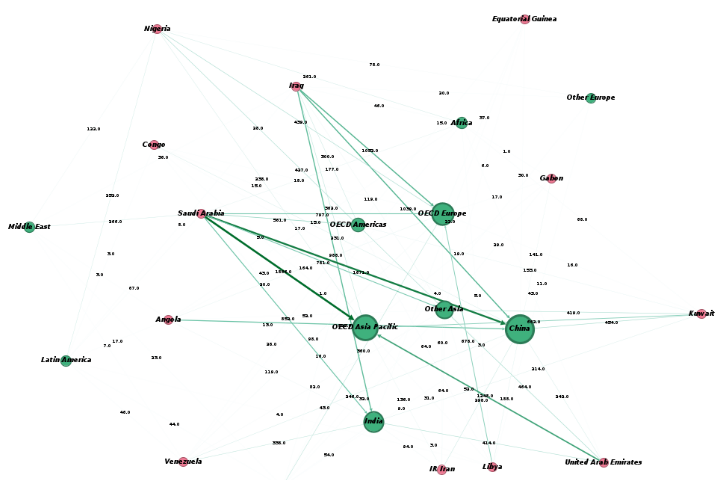

Fig. 4. Crude oil trade network of the year 2019. The year 2019 was plagued with OPEC output cuts and geopolitical supply disruptions. However, the growth in US shale oil production kept the market in check [25].

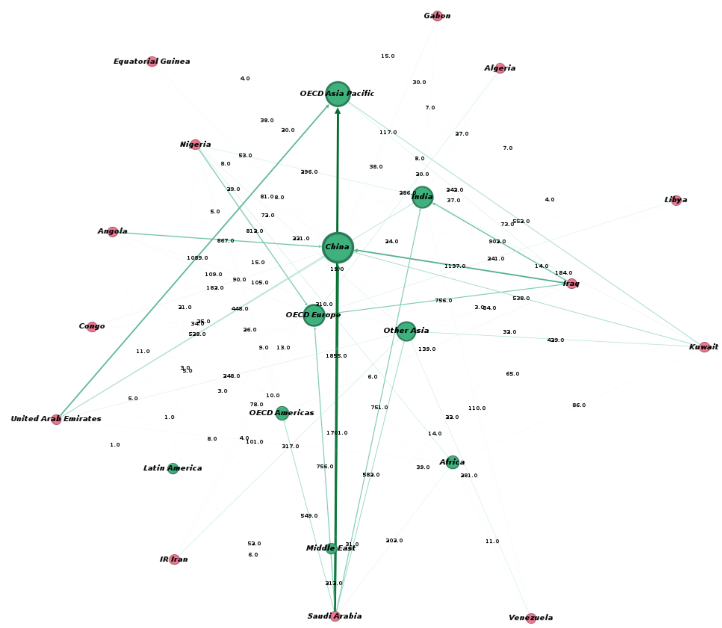

Fig. 5. 2020's crude oil trade network. Onset of Covid-19 pandemic caused the global demand to fall. The crude oil exports fello to the lowest level in 2020 [26].

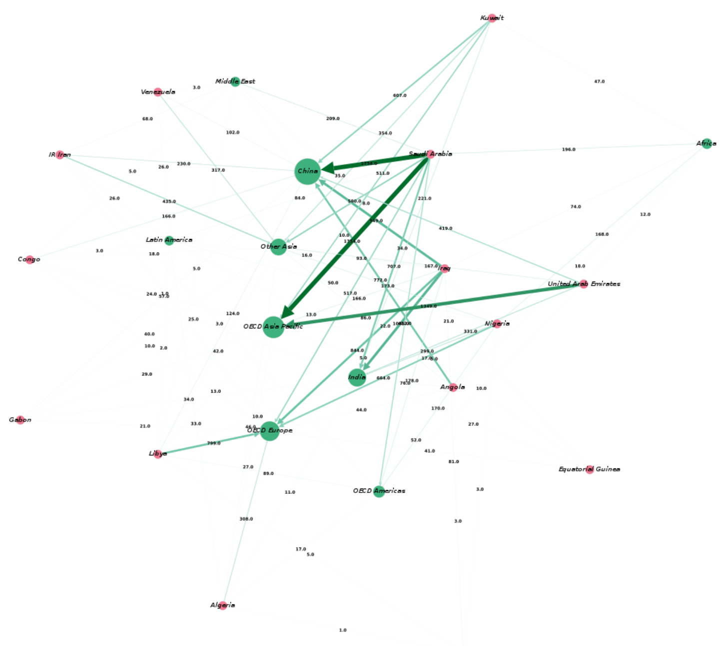

Fig. 6. Crude oil trade network of the year 2021. The crude oil market saw an increase in the global crude oil demand and prices post Covid-19 pandemic, however, due to the global geopolitical events and shift of countries towards renewable energy caused the exports to still be nominal [27].

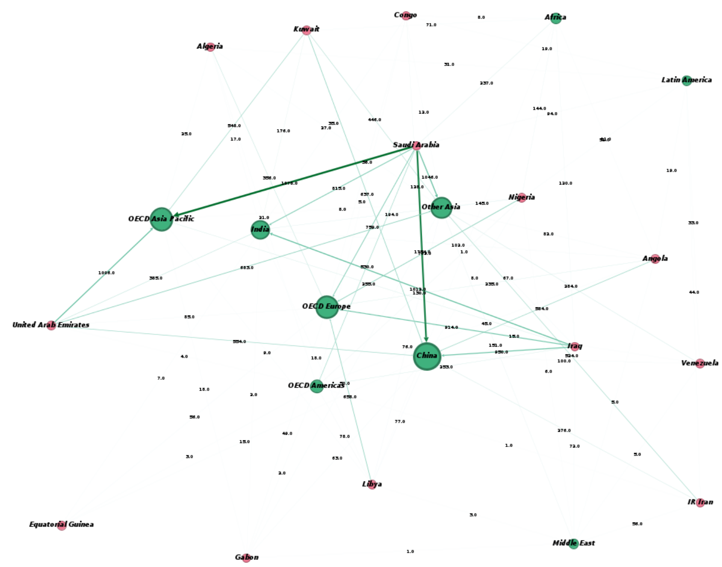

Fig. 7. Crude oil trade network for the year 2022. Due to geopolitical instability the prices have reached a record high amid an OPEC output cut but pre-COVID level of trade is not achieved due to global geopolitical tensions [28].

TABLE I
TABLE TYPE STYLES

Years	Graph network parameters					
	AD	***AWD***	***GD***	***Mod***	***SI***	***ACP***
2016	3.8	984.128	0.158	0.223	295.736	43.29
2017	3.96	970.692	0.165	0.245	294.464	50.80
2018	3.96	914.56	0.165	0.251	310.146	65.23
2019	3.92	899.2	0.163	0.285	291.041	56.99
2020	3.88	788.12	0.162	**0.195**	290.388	39.68
2021	3.8	**786.32**	0.158	0.243	**288.076**	68.17
2022	3.56	855.56	**0.148**	0.197	288.71	**94.53**

Here in Figure 8 X-axis corresponds to the fiscal year, And subsequently Y-axis has values of the parameters in table I normalized on the column basis with the maximum value to allow the parameters to be in the same scale.

The results in Figure 8 show the normalized plots of the values in Table I. Figure 8 shows that the trends improve even after Covid-19 pandemic of 2020 as we can see the overshooting of rates. However, the other metrics recovery is very disproportional when compared to the demand as can be seen from Figure 9 is taken into consideration. The crude demand in Figure 9 shows the global crude oil demand in Million barrel a day for each year from 2016 to 2022. One important observation from Figure 9 is the decreasing control of OPEC oil cartel in the trade.

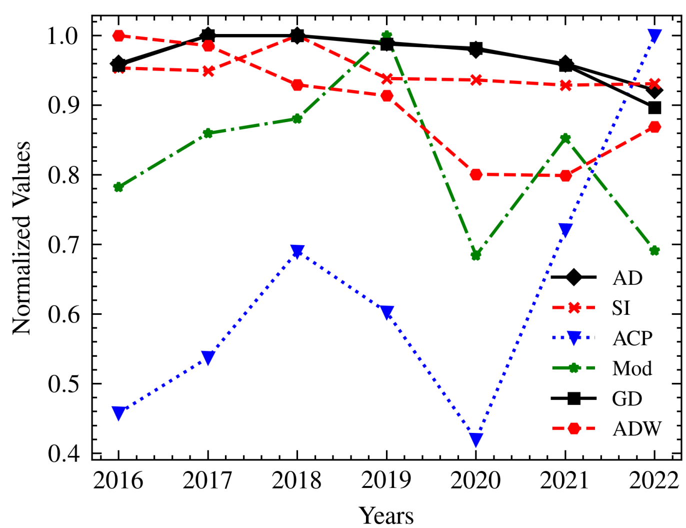

Fig. 8. The normalized statistical values against the years.

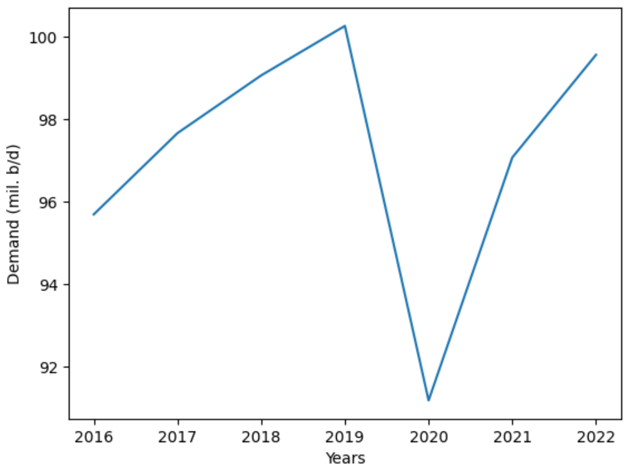

Fig. 9. The global demand of crude oil against the years.

IV. Conclusions and Key Observations

In this paper we collected the crude oil export data from 2016 to 2022 and processed and analyzed using complex network analysis. We used complex networks based data analysis in order to quantify and create a comparison metric between the exporting and importing nations to identify changes in the trade network. Our results shown above reveal that Organization of Petroleum Exporting Countries and Allies (OPEC+) influences and control over the global crude oil market, however, it slowly is losing the control and influence. We also found that Covid-19 pandemic caused the market to crash for a brief period. While the post-pandemic recovery was expected to be quick as per the industry estimated to cross the pre-pandemic levels due to the high demand, however, as we observed from the Average Degree (AD) and Statistical Inference (SI) the recovery was not strong as predicted due to multitude of factors involving the geopolitical tensions, trade restricts, rising interest in renewable energy, rise of non-OPEC members as key players in world level, discovery and development of production capabilities in non-OPEC counties. Furthermore from the graphs, we observed how the OPEC nations are trading and how the export-import relationships changed which reveals a change in the global oil trade network.

V. Limitations and Future scope

One of the major limitations of this research is the prime focus on the exporting nations of the OPEC as even the countries which import crude oil also engage in trade of petroleum products and services, for example India primarily a huge petroleum products net importer post 2020 after sanctions on Russian Federation has become a major exporter of petroleum and hydrocarbon chemicals in various markets [30], furthermore there were major membership changes within OPEC over the years and major deviations of member nations policies from OPEC guidelines which caused disruptions in the trade network.

The study can be further expanded by inclusion of data from the non OPEC oil producing nations to understand full effect of various producers in the market and how they behave with each other and their influence on the market and control over the prices and with proper collection and categorization of data a further fully directed network can be constructed with all nations and with their exports and imports of crude oil and products between each other to quantify the entire world crude oil trade and see any global patterns and draw out trends and future predictions.

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