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Carbon collusion: Cooperation, competition, and climate obstruction in the global oil and gas extraction network

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ABSTRACT

While publicly-available datasets often document how much fossil fuel is extracted within oil-producing countries, they do not generally indicate *who* is responsible. To address this gap, we constructed the Global Oil and Gas Extraction Network, a dataset containing the extraction sites of the 26 largest oil and gas companies, and the quantities extracted annually from 2014 to 2018, accounting for 67% of total production. Using this dataset, we present a first-of-its-kind network analysis of global oil and gas extraction. We find fifty-eight percent of operations involved joint ownership across companies, demonstrating growing interdependence after industry-wide losses in 2016. Countries in which National Oil Companies (NOCs) were active were less likely to host Hybrid state-investor companies, and even less likely to host Investor-Owned Companies (IOCs), while certain Hybrids and IOCs tended to operate in the same countries; both trends became more pronounced between 2014 and 2018. Reflecting colonial legacies, the seven Big Oil companies, headquartered in either the US or Europe, extracted oil and gas from the most countries. These findings reveal a complex global network of strategically aligned actors, indicative of tacit and explicit transnational industry-state collusion to obstruct climate policies. These findings additionally underscore the need for comprehensive data to support a managed fossil fuel phaseout.

1. Introduction

Amid the growing urgency surrounding global climate change (Byrnes, 2020; IPCC, 2022), concerted efforts to constrain fossil fuel supply have been repeatedly contested by both states reliant on revenues from oil and gas extraction and by politically powerful transnational fossil fuel companies, whose business models rely on continued fossil fuel exploration and extraction (McKie, 2021). Although the past decade has seen some progress towards reducing greenhouse gas emissions by deploying renewable energy and increasing the electrification of transportation and heating, at the same time oil and gas extraction has surged (Mills, 2020). This increase is due in part to expansion of high-volume hydraulic fracturing (fracking) and horizontal drilling (primarily in the U.S.), permitting the large-scale extraction of previously inaccessible shale oil and gas reserves. This controversial method (Howarth et al., 2011) has propelled the U.S. to become the largest producer of petroleum and natural gas in the world, surpassing Russia as the leader in natural gas extraction in 2009 and Saudi Arabia in petroleum extraction in 2013 (Maizland and Siripurapu, 2022).

The financial gains associated with global oil and gas extraction have resulted in fossil fuel interests exerting powerful influence over political processes in many countries (Stephens, 2020), blocking efforts for a managed phaseout of fossil fuel extraction and carbon-based energy use. Fossil fuel interests have also funded decades of coordinated strategic investment to deny and cause confusion about whether fossil fuels contribute to the climate crisis and to delay or halt climate policies designed to reduce fossil fuel reliance to decrease carbon dioxide emissions (Brulle, 2018; Li et al., 2022; MacNeil and Paterson, 2020). Governments in aggregate around the world still plan to permit or directly “produce more than double the amount of fossil fuels in 2030

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than would be consistent with limiting warming to 1.5 °C," which would lead to an increase global oil and gas extraction until at least 2050 (SEI et al., 2023:2). With many oil and gas companies now openly acknowledging the need for an energy transition toward a renewable-based future, there are growing claims of greenwashing as oil and gas companies continue to expand fossil fuel exploration and extraction around the world (Lockwood and Lockwood, 2022). While countries that are heavily involved fossil fuel extraction have pledged to achieve net-zero emissions and launched some emissions reduction initiatives, "none have committed to reduce coal, oil, and gas production in line with limiting warming to 1.5 °C" (SEI et al., 2023:2).

At the same time, there have been growing efforts to track policies to constrain extraction and push for greater industry accountability for the social-ecological impacts of fossil fuel extraction. The Fossil Fuel Non-Proliferation Tracker documents supply-side policies, including moratoria, bans, and limits, as well as subsidy reductions and divestments by third-party organizations (Uenal and Daley, 2023). The Fossil Fuel Cuts Database specifically focuses on policy initiatives to constrain fossil fuel extraction (Gaulin and Le Billon, 2020). The environmental injustices inherent in global oil and gas extraction are included in the Environmental Justice (EJ) Atlas, which documents environmental conflicts (Temper et al., 2015; Martínez-Alier, 2023).

A better understanding of fossil fuel supply, and the social-ecological impacts of oil and gas extraction, is also essential to confront the power of vested fossil fuel interests around the world and their collective motivation and ability to obstruct and derail meaningful efforts to achieve large-scale energy transition across national borders (Lamb et al., 2020; Oreskes, 2015; Supran and Oreskes, 2017, 2020, 2021). Among notable recent grassroots efforts to curb fossil fuels is the Fossil Fuel Non-Proliferation Treaty (Newell and Simms, 2020). The Production Gap report, co-authored by Stockholm Environment Institute and United Nations Environment Program, among others, and cited in the preceding paragraphs, highlights the contradiction between emissions reduction pledges and the CO2 equivalent extracted in fossil-fuel-producing countries. First issued in 2019, it has since been updated regularly; most recently in 2023 with the subtitle: "Phasing down or phasing up?: Top fossil fuel producers plan even more extraction despite climate promises" (SEI et al., 2023). The urgency of the imperative to confront the power of vested fossil fuel interests has been underscored by the failure of thirty years of the United Nations Framework Convention on Climate Change (UNFCC) process to restrict fossil fuel supply, as demonstrated by the 2022 27th Conference of the Parties (COP27) in Egypt to directly acknowledge the need to phase out fossil fuels in the final text language. The 2023 28th Conference of the Parties (COP28) in Dubai likewise did not call for a phaseout of fossil fuels in the final text language, although it did approve a roadmap for 'transitioning away from fossil fuels' (UNSDG, 2023).

1.1. *Tracking global extraction: company vs nation-state*

Against this recent backdrop, and a much longer history of the exertion of political power worldwide by fossil fuel interests (Newell and Paterson, 1998; Mitchell, 2009), the lack of comprehensive publicly available data detailing extraction, processing, and sales at the company level has slowed down policy efforts to phase out fossil fuels. The handful of major publicly available datasets with detailed information on fossil fuel production, consumption, and trade patterns (e.g. BP's Statistical Review of World Energy, OPEC's Annual Statistical Bulletin, UN Comtrade's International Trade Statistics Database, and the US Energy Information Administration data collections) are provided at the national or subnational level, rather than at the company level, further obscuring already opaque transnational interactions.

Moreover, the company-focused data that are available have often been the target of high-level obstruction (Gamper-Rabindran, 2022; Maddow, 2021). While there exist extensive proprietary datasets detailing global extractive activity by oil and gas companies at the field level (Rystad Energy, 2023), no such comprehensive dataset is publicly available, although efforts by the Global Energy Monitor (Global Energy Monitor, 2023a, 2023b) and the Corporate Mapping Project (Carroll, 2021) represent important steps in this direction. Nonetheless, additional information and transparent analysis is urgently needed to allow policy-makers, advocacy groups, and researchers to assess the intricate web of oil and gas extraction, to develop coordinated fossil fuel phaseout strategies, and to more fully gauge the distribution of social, environmental, and political impacts (Hawkes et al., 2023; Muttitt and Kartha, 2020).

Third party watchdog organizations addressing the activities of oil and gas companies tend to focus on one process within the wider supply chain network (such as the Global Registry of Fossil Fuel database of CO2-equivalent embodied in reserves and extraction (West and Schuwerk, 2022)), or on the activities of one company (e.g. West, 2014, focusing on British Petroleum). Likewise, LINGO's valuable global map of 425 "carbon bombs," defined as proposed or existing coal, oil or fossil gas projects with a potential to emit over a Gigaton of CO2, (Kühne et al., 2022) aggregates its findings to the national level.

The Global Oil and Gas Extraction Tracker (GOGET), one of several databases and collection of wiki pages compiled by Global Energy Monitor, does include the operator, owner and parent company of oil and gas units, usually at the field level (Global Energy Monitor, 2023a). With the exception of GOGET and other GEM databases, however, the activities of the major firms engaged in fossil fuel extraction are rarely tracked in publicly available datasets in any consistent manner, obscuring the central role of transnational private and hybrid state-private interests in a complex global regulatory and political landscape.

In this research, we developed a new spatially-explicit dataset of the Global Oil and Gas Extraction Network (GOGEN), an original dataset that has not previously been assembled or characterized, containing more than 7200 records for exploration, reserves, extraction, refining, and sales for the 26 most extractive companies during the period between 2014 and 2018. The 26 companies included in this dataset fall into three general categories:1) national oil companies (NOCs) 2) Investor-Owned Companies (IOCs) and 3) 'Hybrid' companies (de Graaff, 2011), which are partly state-owned and partly owned by private investors; in some cases banks and, notably, other oil companies have significant holdings. Using the GOGEN dataset, we present an integrated description of high-level global oil and gas extraction (the extraction layer only) weighted by the volumes extracted from each country by these companies. We then analyze the resulting network according to established methods and highlight key trends and network hotspots.

2. Data and methodology

In this section we provide the theoretical foundations for the GOGEN, situating our contribution within the wider literature on global production networks. We then describe how the GOGEN dataset was compiled, the origin of original data, the structure and format of the dataset, protocols for managing missing data, and information about its availability. We further describe the methodological approach used in the network analysis, how the formal input data were generated from the GOGEN dataset, the types and structure of the input data that were used for the network analysis, and how missing data is represented in the network model.

2.1. *Theoretical foundations*

The Global Oil and Gas Extraction Network (GOGEN) draws on and expands the Global Production Network (GPN), a non-mathematical description of resource-based development widely used in economic geography. Coe et al. (2008: 272, 274) note that economic *networks* "reflect the fundamental structural and relational nature of how production, distribution and consumption of goods and services" are organized; *production networks* encapsulate “the nexus of interconnected functions, operations and transactions through which a specific product or service is produced, distributed and consumed” and *global production networks* consist of “interconnected nodes and links extend spatially across national boundaries and, in so doing, integrate parts of disparate national and subnational territories.” Subsequent definitions highlight the involvement of both “economic and non-economic actors, coordinated by a global lead firm and producing goods or services across multiple geographical locations for worldwide markets.” This “more ambitious round of theoretical innovation,” termed GPN 2.0, sought to develop a “framework for explaining patterns of uneven development – both between and within countries – in the contemporary global economy” (Yeung and Coe, 2015: 3–4). A more recent review, addressing extensions and critiques of the GPN 2.0 approach, identifies five “constituent outsides” relating to a) the state, b) finance, c) labor, d) environment, and e) development. The GPN 2.0 approach has been further characterized as a “*necessary* but not *sufficient* analytical tool for understanding uneven development” (Coe and Yeung, 2019:793).

The GOGEN presented here draws on and expands the GPN model for oil presented by Bridge (2008), which identifies two defining tensions influencing the organizational structure and geography of the oil industry: 1) the tension between resource-holding states and resource-seeking firms and 2) the distribution of value between producers (both states and firms) and consumers. Bridge also identifies key processes in the production network, spanning the life cycle of oil, from exploration to emissions. Although Bridge’s work relied on national-level production and consumption data from BP’s Statistical Review of World Energy and did not include other significant social, political and environmental dynamics, it was notable in prioritizing inter-firm and firm-state relationships. More recent studies that apply the GPN approach to oil and/or gas production focus on: a) the territoriality of liquified natural gas (LNG) production networks (Bridge and Bradshaw, 2017); b) the efforts of Brazilian parastatal Petrobras to exploit offshore deposits in collaboration with overseas partners such as Chevron, Halliburton and Shell (Scholvin, 2017); and c) the contrasting role of cities in resource-poor and resource-holding states, exemplified by Singapore and Jakarta, in the World City Network (WCN) of the upstream oil and gas industry (Breul, 2019; Breul et al., 2019).

In developing the data model for the GOGEN, we conceptualize the processes of exploration, extraction, transportation, refining, processing, consumption, and emissions identified in Bridge’s GPN model for oil as network layers (Fig. 1). Our data model is intended to facilitate network modeling, and both delineates and highlights the role of states, firms, processes, and products in the network. Layers for reserves and development are included as additional processes in the dataset and consumption is quantified as retail sales by oil and gas companies. GPN state and firm functions (Bridge, 2008) are listed for reference in Fig. 1a. They are largely based on the functions of privately-owned companies; national oil companies have the potential to play a different role, whereby they may be more directly accountable to the public through their ownership structure, rather than to private shareholders.

2.2. *Dataset construction: compiling the global oil and gas extraction network for 2014–2018*

Dataset Overview: The GOGEN dataset contains more than 7200 records for exploration, reserves, extraction (referred to as ‘production’ in Bridge’s original model), refining, and sales between 2014 and 2018. In order to focus on temporal as well as spatial dynamics, we limited this initial data collection effort to the 26 largest oil and gas companies in terms of quantity extracted. These 26 companies together accounted for approximately 67% of annual global extraction during the period from 2014 to 2018 (55700 of 81900 kboed). We focused this initial round of data collection on the extraction activities of these companies: approximately 5300 of the >7200 records pertain to extractive activity. The remaining records pertain to exploration and reserves, as well as mid- and downstream operations. Data for these additional processes have not been compiled for all 26 companies and will be supplemented in future iterations, serving as the basis for follow-up studies; the data model facilitates the construction of a multilayer network that encompasses the other processes as well, spanning the full life cycle/supply chain for oil and gas. (While the GOGET dataset compiled by Global Energy Monitor focuses on the field level, the original GOGEN dataset presented here includes quantities extracted by the top 26 oil and gas companies on an annual basis, systematically tracking their extractive activities worldwide and clearly conveying data gaps in company reporting.)

Temporal Range: The pivotal 5-year period from 2014 to 2018 was selected for this analysis for multiple reasons. For one, it avoids the anomalies produced by the COVID-19 pandemic. Moreover, 2014–2018 was a time of major upheaval in the global oil and gas industry, including the run-up to the historic Paris Climate Accord and its immediate aftermath. The Paris Agreement to limit global warming to 1.5 °C above pre-industrial levels was passed in December 2015 and 2016 was “one of the most eventful in terms of major market developments, asset transactions and developments in public policy” (Blackmon, 2016). Moreover, this version of the dataset is intended to serve as an initial effort, with successive releases extending backward to 2000 and

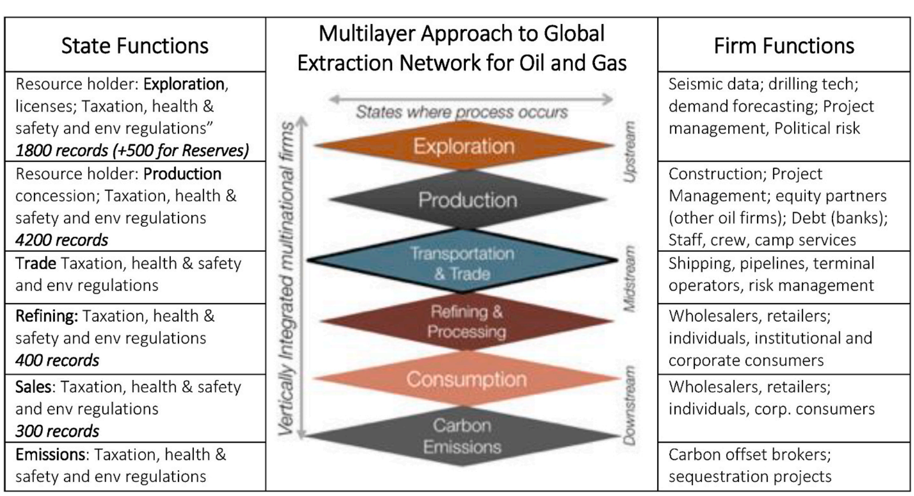

Fig. 1a. Multiplex representation of the generalized global extraction network for oil and gas used in this study. The network analysis presented here focuses on the Extraction layer (referred to as ‘Production’ in the Bridge model) from 2014 to 2018 and distinguishes between company types (National, Investor-Owned, and Hybrid).

forward to the current year, with annual updates thereafter.

Data Sources: The GOGEN dataset was compiled using publicly available data sources including annual reports, operating statements, and SEC filings of the top 26 oil and gas companies based on millions of barrels of oil equivalent per day (mboed) as ranked in 2016. Our reliance solely on public data sources emphasizes the paucity of data concerning firm-level activities compared to national-level data on fossil fuel extraction. Annual reports and SEC filings provided the bulk of the data sources for hybrid and investor-owned companies.

The Natural Resource Governance Institute (NRGI) National Oil Company Database (NRGI, 2020) provided the majority of data for the NOCs: (ADNOC, Basra Oil Company, KPC, NIOC, NNPC, Qatar Petroleum, Pemex, PDVSA, Saudi Aramco, Sonatrac), but annual reports were also consulted if available. A total of 149 of the 4215 records in the GOGEN extraction table were obtained from the NRGI dataset (indicating how much more active IOC and Hybrid companies are in many different countries). Gaps in the NRGI dataset were supplemented by other sources where available, such as the 2018 Pemex Statistical Yearbook.

Given the much higher accuracy of proprietorial industry data sources than public sources, figures were validated where possible using data from limited access to the industry-standard Rystad Energy U-Cube database (Rystad Energy, 2023) and The Carbon Underground 200 (Fossil Free, 2020). Data limitations are discussed at greater length in Appendix A.

Data model: Each record in the dataset includes the process/layer [exploration| reserves | development | extraction | transport | refining | sales| emissions], company name, the country of operation, the quantity (if available), unit, exact location if given, year, information source, whether the operation was a joint venture and venture partners if listed (Table 1).

Data compilation process: The data compilation process consisted of several concrete steps: 1) Identification of a suitable data source for each of the 26 companies annually over the 5-year temporal range; 2) Extraction of relevant data from original source and restructuring into the format specified in the data model; 3) Harmonization of region and country names. (Unit standardization was completed during the restructuring of data inputs for network analysis described in the following section.) Data were compiled using statistical software environments R and JMP and the Python programming language. Original data source retrieval and unit standardization was coded in R; original documents from which the data were compiled were also stored in a local repository. Where extraction data was included in table form, data restructuring was also coded in R; in some cases, table-based data were restructured manually in JMP. If the original record was not in table form, data restructuring was done manually in Excel, and the text from which the record was constructed was stored in the 'Notes' field in the dataset.

Data availability: A copy of both the GOGEN and the network inputs for the analysis described below is available as supplementary information for this paper. This dataset (and updated versions) will also be available on the OSF data repository. Our repository of the original data sources (primarily company annual reports) used to compile the GOGEN may also be shared upon request.

2.3. Methodology: network analysis

In this section, we describe in further detail the methodological approach used in the network analysis of the GOGEN dataset presented in this paper. After providing an overview of the utility and aims of network analysis and its suitability for analyzing the global oil and gas extraction network, we describe the network model we used, and how the formal data inputs for this network analysis were generated from the GOGEN. We also identify instances of missing data and describe our approach to handling missing data.

Network models can be used to represent physical networks such as road systems, telecommunications, and electrical grids, as well as networks comprised of social relationships, such as social media contacts, paper co-authors, business clients, or donors to political campaigns. In their simplest form, network models, which can be used to depict either physical or abstract networks, are comprised of discrete entities ('nodes') and the interactions ('edges') between them. A bipartite network represents the relations among two different sets of nodes, with edges only occurring between nodes of different sets. Multiple types of interactions can be also modeled using a layered, or 'multiplex' network, wherein each layer represents a different type of interaction, and the nodes are constant across layers (Baggio et al., 2016). Interdependencies between layers can affect the entire system, indicative of behavior that cannot be predicted by studying each layer in isolation.

The complexity of oil and gas extraction networks lends itself to multiple types of network modeling, depending on the rules used to define nodes, edges, and layers. The GOGEN database was structured to facilitate network analysis in which companies and countries could be treated as distinct node types. As mentioned above, we focus the network analysis presented here on the extraction layer of the dataset only, which includes publicly available data for all 26 companies. The data inputs for this network analysis were derived from the GOGEN, and consisted of two data tables used to construct the network, the first containing a list of network nodes, and the second containing a list of network edges.

- Node List: This input data table includes the complete list of extractive companies and resource-holding countries in the network, with "True" indicating the node type "Company," and "False" indicating the node type "Country," to facilitate the creation of a bipartite network. For companies the third column indicates the type of company: Big Oil, Hybrid, and NOC, this data was used for some of the network models presented in this paper. The node list has a total of 112 entries (26 companies and 86 countries).
- Edge List: This standardized input data on extraction includes separate records for each country in which a particular company extracted oil and gas, and the amount, type, and year extracted. At this stage, the units used to specify quantities of the oil and gas extracted were standardized from the units given in the original data sources, to the following: thousands of barrels per day (kbd) for total hydrocarbons and for liquids (primarily crude oil), and thousands of barrels of oil equivalent for gas (kboed). [NRGI data used kboed for all fuel types; this unit was carried over for the 51 records including liquids for NOCs from the NRGI that were used in the GOGEN.] The edge list has 2829 records, and contains the following fields: Company, Country, Fuel Type, Weight (Quantity), Unit, and Year. It is an aggregation of the GOGEN extraction data to the country level (some companies provided subnational data for volumes extracted annually), and therefore the edge list contains fewer records than the GOGEN extraction data table.

For this analysis, we constructed networks focusing on.

- Network changes over time: Bipartite networks were constructed with extractive companies and resource holding countries forming

Table 1
Data model for the Global Oil and Gas Extraction Network Dataset.The column headers represent fields in the dataset and the empty row represents a sample record.

Process	Company	Country	Type	Weight	Std Unit	Lo-cation	Data Source	Notes	Joint Venture Status

the two different node types; edges were drawn if a particular company extracted oil or gas from a particular country. Each year from 2014 to 2018 was represented as a separate layer. Three separate temporal networks were constructed, one each for oil, natural gas, and total hydrocarbons.
- Differences in behavior based on company type: Separate layers representing national oil companies (NOCs), hybrid state-investor companies, and fully investor-owned companies (IOCs Big Oil + the Russian-headquartered Lukoil) were repeated for successive years from 2014 to 2018 as separate multiplex networks.

These networks were also *directed* and *weighted*: an edge was drawn *from* a country *to* a company when a company extracted oil or natural gas from a country; edges were weighted by volumes extracted (if this data was available). We analyzed these networks using the following metrics: 1) network centrality, in terms of the strength of each node (how much oil and gas flows *from* each country *to* each company), as well as the degree of each node in the network (the number of countries in which companies extract oil), 2) correlation among multiplex networks, treating years and company types as network layers, and 3) community detection using the Louvain method. For the analysis of network centrality each year is represented as a different layer, and separate networks were constructed for each fuel type; Liquids, Gas, and Total Hydrocarbons. Appendix B provides additional details about how the network metrics presented in this analysis were calculated.

Modeling tools: Multilayer network visualization and analysis for the results presented in Section 3.2 and 3.3 were undertaken in MuxViz (De Domenico et al., 2015), which runs on R and Octave. The results of the analysis of community detection within the network presented in Section 3.4 was undertaken in R using the igraph package (Csardi and Nepusz, 2006).

2.3.1. Missing data and other challenges in network representation

As noted above, the level of detail provided for each company varied significantly, with investor-owned companies (IOCs) accountable to shareholders providing relatively more information in annual reports about the locations in which they operate and how much they extracted each year than national oil companies. Appendix A provides more information about the gaps, inconsistencies and ambiguities in the data, which in some cases is overtly politically charged. Shell, for example, lists an "Other" category comprised of "countries where extraction was lower than 7300 thousand barrels *or where specific disclosures are prohibited*" (Royal Dutch Shell, 2019: 48). Given these limitations, our results are presented as a partial but nonetheless useful and illuminating representation of a complex web of public and private actors involved in oil and gas extraction around the world.

'Hybrid' companies (partially state-owned and partially privately-owned) tended to provide a list of countries in which they operate, but not the quantity that was extracted each year. This category posed the most difficulty for the construction of weighted networks, where an extractive relationship between a given company and country could be established (usually over a multi-year period), but the amount extracted annually was missing. However, several factors make this issue relatively manageable for the purposes of the network analysis presented here.

- A relatively small number of records fall into this category. At the country level, to which the analysis was aggregated, 13% of entries had missing weights (375 of 2829 records).
- As noted above, these cases fit a general pattern. The most frequent scenario in which a company reported a location in which it was active but not the quantity extracted was in the case of a Hybrid company (generally based in Russia or China) reporting on a relatively small number of recent ventures (involving about 4–5 countries) outside of its home territory.
- The weights involved are likely to be relatively small. The cases described above can generally be assumed to comprise a small proportion of the company's total volume. In this case, even when the weight was missing, the relationship was still represented in the network, but not assigned a weight.
- Only two companies did not fit this general pattern. Petronas, Malaysia's state-owned oil and gas company, reported extractive activities in 23 countries but did not indicate amounts extracted by country at all. CNOOC, the overseas arm for China's oil and gas extraction published weights at the aggregate regional level only.

In future analyses, we will revisit these protocols to determine if other approaches to handling missing data may provide additional insight into the network. For full transparency, Appendix A also includes a table describing the records in the edge list used in the network analysis that contained missing weights.

3. Results

3.1. A system-wide overview of global oil and gas extraction

The 26 companies covered in the GOGEN fall into three general categories:1) NOCs 2) IOCs and 3) 'Hybrid' companies (de Graaff, 2011), which are partly state-owned and partly owned by private investors. Four of the seven IOC companies are headquartered in European countries (BP in Great Britain, Royal Dutch Shell in the Netherlands, TotalSA in France, and EniSpa in Italy) and the other three (ExxonMobil, Chevron and ConocoPhillips) are headquartered in the U.S. (Table 2). All seven of these IOCs (also known collectively as 'Big Oil') are headquartered in countries that do not have nationalized or hybrid firms. With the exception of Brazil, all countries with fully state-owned national oil companies are also members of the Organization of Petroleum Exporting Countries (OPEC).

Together these 26 companies directly employed more than 3 million people in 2018 (Table 2), but the reach of the industry is more extensive than direct employment figures indicate. In the United States, for example, the oil and gas industry accounted for up to 5.6% of total employment in 2015, combining operational and capital investment impacts, and amounting to 10.3 million full-time and part-time jobs, according to a study commissioned by the American Petroleum Institute (PwC, 2021). Globally, the oil and gas drilling sector, comprising companies that explore, develop, and operate oil and gas fields, alone made up around 3.8% of the global economy, or $3.3 trillion of the estimated global GDP of $86 trillion in 2019. In 2023 the size of the global oil and gas market, including upstream activities and downstream products, was $7.3 trillion; this is expected to grow to $8.7 trillion by 2027 (The Business Research Company, 2023).

3.2. Network centrality metrices: flows among countries and companies

Having provided a system-wide overview of these 26 companies, we now turn to the results of the network analysis of the GOGEN dataset described in Section 2. There are notable differences in the network centrality and node strength (weighted degree) of total hydrocarbon extraction in aggregate, as well as patterns that emerge when considering oil and more regionally bounded natural gas networks separately (Table 3).

3.2.1. Total hydrocarbons

3.2.1.1. Volumes extracted (Node strength). The special role of Saudi Arabia in the oil and gas extraction network (Mitchell, 2013) is evident in the quantity of total hydrocarbons going to Saudi Aramco, compared to the next largest producer, Gazprom (Fig. 2a). The National Iranian Oil Company (NIOC), Rosneft, and PetroChina round out the most

Table 2
Key figures describing the top 26 global oil and gas producers as measured by millions of barrels of oil equivalent produced per day in 2018. NOCs are shown in pink, Hybrids in gray, and IOCs in orange.

Company	Country HQ	Year Founded	Type	Hydrocarbon Prod. in 2018 (mboed)	Employees in 2018
1. Saudi Aramco	Dhahran, SA	1933	NOC/OPEC	13.60	70762
2. Gazprom	Moscow, Russia	1989	Hybrid: 50% state owned	10.19[c]	466100
3. Rosneft	Moscow, Russia	1993	Hybrid: 50% state owned	5.82	302100
4. ADNOC	Abu Dhabi, UAE	1971	NOC/OPEC	4.67[a]	55000
5. National Iranian Oil Company	Tehran, Iran	1951	NOC/OPEC	4.50[a]	104000
6. Petrochina	Beijing, China	1999	Hybrid: 82% State-owned	4.09	506000
7. Exxon Mobil	Irving, TX	1911	IOC/Big Oil	3.83	69600
8. BP	London, England	1909	IOC/Big Oil	3.68	74000
9. Royal Dutch Shell	The Hague, Netherlands	1907	IOC/Big Oil	3.67	18000
10. Iraqi Oil Ministry	Bagdad, Iraq	1966 1987 2018	NOC/OPEC	3.59[a]	
11. Kuwait	Kuwait City, Kuwait	1980	NOC/OPEC	3.19	10984
12. Chevron	San Ramon, CA, USA	1879	IOC/Big Oil	2.93	48596
13. TotalSA	Courbevoie, France	1924	IOC/Big Oil	2.78	104000
14. Petrobras	Rio de Janeiro, Brazil	1953	Hybrid: 64% state-owned	2.77	62700
15. Petroleos de Venezuela	Caracas, Venezuela	1976	NOC/OPEC	2.73[a]	
16. Pemex	Mexico City, Mexico	1938	Hybrid: 75% state-owned	2.58	124660
17. Lukoil	Moscow, Russia	1991	IOC	2.35	103600
18. Petronas	Kuala Lumpur, Malaysia	1974	NOC	2.32	49911
19. Sonatrach	Algiers, Algeria	1963	NOC/OPEC	2.27	120000
20. Equinor	Stavanger, Norway	1972	Hybrid: 67% state owned	2.11	20525
21. Qatar Petroleum	Doha, Qatar	1974	NOC/OPEC	1.92	14000
22. EniSpa	Rome, Italy	1953	Big Oil	1.85	33000
23. CNOOC	Beijing, China	1982	Hybrid: CNOOC state/CNOOC Ltd investor-owned	1.30	99000
24. ConocoPhillips	Houston, TX, USA	1875	Big Oil	1.28	10800
25. Sinopec	Beijing, China	2000	Hybrid: Sinopec Group state owned/Sinopec Ltd investor-owned	1.24	249000
26. Nigerian National Petroleum Company	Abuja, Nigeria	1977	NOC/OPEC	1.19	

[a] 2018 extraction figures not available; 2017 used.
[b] Total national extraction for Iran from BP Statistical Review used in lieu of company publications.
[c] plus equity affiliates.

Table 3
Each node and fuel type (total hydrocarbons (THC), crude oil, natural gas) as single layer networks. Nodes appearing in at least one of the five years from 2014 to 2018 are included in N.
The total hydrocarbon category is more comprehensive than liquids or natural gas because there are some firms for which country and field-level extraction is not disaggregated into oil and gas.

Metric	Big Oil	Hybrid	NOC	Big Oil	Hybrid	NOC	Big Oil	Hybrid	NOC
	THC	THC	THC	Crude Oil	Crude Oil	Crude Oil	Gas	Gas	Gas
Companies (N)	7	9	10	7	9	10	7	9	10
Countries (N)	87	36	14	54	20	12	71	18	10
Edges *m*	768	412	52	624	107	51	667	89	46
Average degree	11.0	5.72	2.16	8.91	4.1	2.3	10.1	3.7	2.3
Node strength (weighted degree) Sum of weights/N /5 = kboed per year	260	400	1709	144	484	1322	118	491	612
Pearson Correlation Assortativity	−0.85	−0.72	−0.59	−0.87	−0.61	0.34	−0.78	−0.62	1
Community Detection: Modularity	0.07	0.05	0.07	0.06	0.07	0.07	0.08	0.07	0.07

extractive five companies during this period. ExxonMobil and BP occupy the sixth and seventh places respectively, although in 2018 ExxonMobil outproduced PetroChina to be the fifth largest extractor that year (Fig. 2a, red segments). A different narrative emerges from the country perspective (Fig. 2b); here the largest volume of total hydrocarbons flowed from Russia, primarily to its hybrid state-private companies Gazprom and Rosneft (in the second and fourth spots respectively for total hydrocarbon extraction), as well as to the investor-owned Lukoil. (It is important to note that while the 26 companies depicted in this network collectively extract the largest volumes of total hydrocarbons from Russia and Saudi Arabia respectively, smaller firms, responsible for the remaining one-third of extraction, were more active in the U.S., accounting for its greater overall total extraction.)

3.2.1.2. Number of countries in which companies extract oil and gas (node degree). While the volume of inputs and outputs highlights the importance of Russia, Saudi Arabia, China, and their respective national and hybrid companies, an examination of node degree highlights the central role of IOCs in the global network. This metric represents the number of *countries* in which each *company* was actively extracting oil and gas (in-degree). IOCs occupy the first six spots (Fig. 3a). Conversely, the number of companies extracting oil and gas from each country (node out-degree)

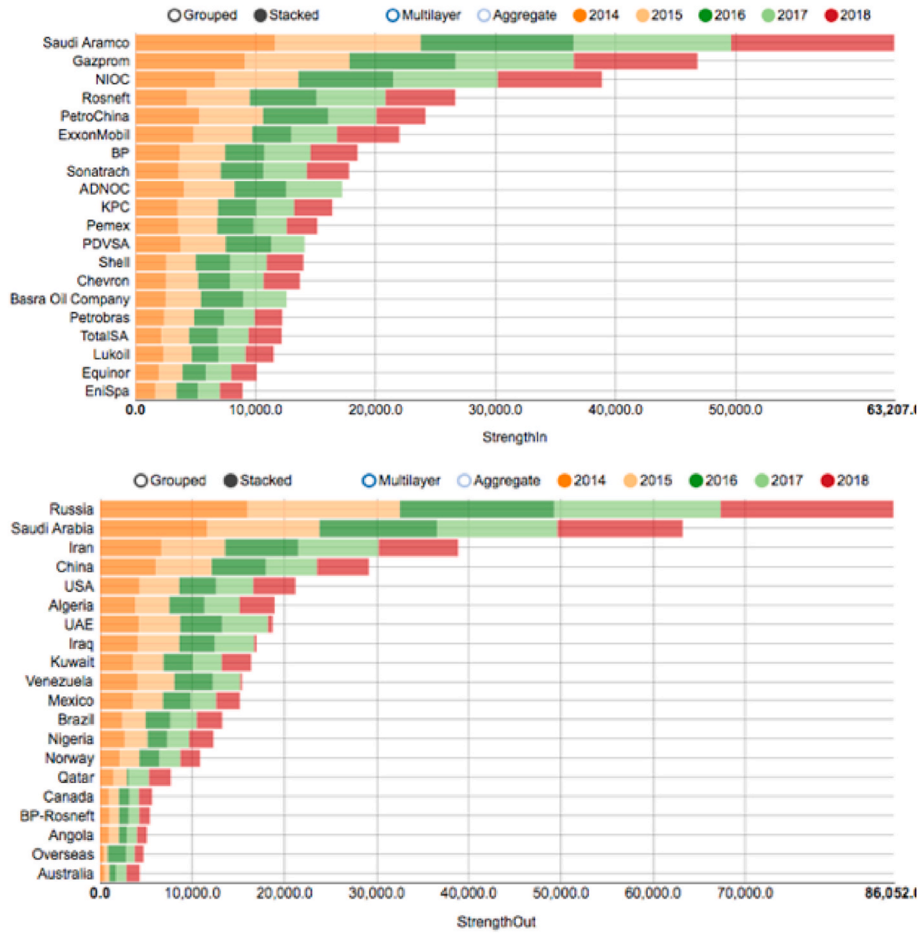

Fig. 2a and b. Total Hydrocarbon Extraction, Network Node Strength: 2014–2018. a) Strength in: total flow of total hydrocarbons to all companies by country by year. b) Strength out: total flows from all countries to the Top 26 companies.

shows Canada had the largest number of top 26 companies extracting oil and gas, followed by the USA and the UK (Fig. 3b). Fig. 3 depicts both the aggregate number of unique countries in which each firm operated during the entire period from 2014 to 2018 and the number of countries they operated within during each year.

3.2.2. Crude oil and other liquids

3.2.2.1. Volumes extracted (Node strength). The crucial Saudi role in extraction is underscored by the amount of oil originating there (Fig. 4a) that went to its national oil company, Saudi Aramco (Fig. 4b); this quantity was twice that of the next largest oil producer, NIOC/Iran. NOCs rounded out the fourth, fifth and seventh positions before Big Oil appeared the in sixth and eighth places. By country, Russia was second to Saudi Arabia, followed by Iran, Iraq,[1] China, Kuwait, the United Arab Emirates, highlighting the pivotal role of the Middle East in global oil extraction and the prominence of Russia and China; this group was followed by the Western Hemisphere extractors (Fig. 4b).

3.2.2.2. Number of countries in which companies extract crude oil (node degree). The seven Big Oil companies dominated node in-degree ranking for crude oil and other liquids, followed by Gazprom, PetroChina and CNOOC, again illustrating the expanding role in worldwide extraction of Russia and China (Fig. 5a). From the country perspective (node out-degree), the U.S. hosted the most companies, particularly in the Gulf of Mexico. The UK and Canada are next, followed by Norway, Nigeria, Russia, China, Iraq, and Venezuela. Fig. 5 depicts both the aggregate number of unique countries in which each country extracted crude oil and other liquids during the entire period from 2014 to 2018, as well as the number of countries they operated within during each year.

3.2.3. Natural gas

Gas extraction was dominated by Gazprom, followed by NIOC, Saudi Aramco, Algeria's Sonatrach, and PetroChina, nearly tied with ExxonMobil (Fig. 6a). (Qatar Petroleum would be in the top group if accurate data were available for 2014–2016.) In 2018 Gazprom accounted for 12% of the world's natural gas extraction, holding 16% of the world's reserves and 71% of the reserves in Russia (Gazprom, 2019).

Russia dominated extraction by country, more than double that of Iran (second), while the U.S. ranked sixth (Fig. 6b), even though the Russian Federation produced 64.74 bcf and the U.S. produced 89.1 bcf in 2018 (British Petroleum, 2020). This discrepancy can be explained in terms of how much of each country's gas went to the major producers: whereas ExxonMobil produced 2.78 bcf/day in the U.S. in 2018, in the same year Gazprom produced 48.24 bcf per day in Russia. An examination of the node out-degree shows a different picture than node strength: here the U.S. and UK were tied at the top, with Russia ninth (Fig. 7b). Fig. 7 depicts both the aggregate number of unique countries in which each country extracted natural gas during the entire period from 2014 to 2018, as well as the number of countries they operated within during each year.

[1] 2018 data not available.

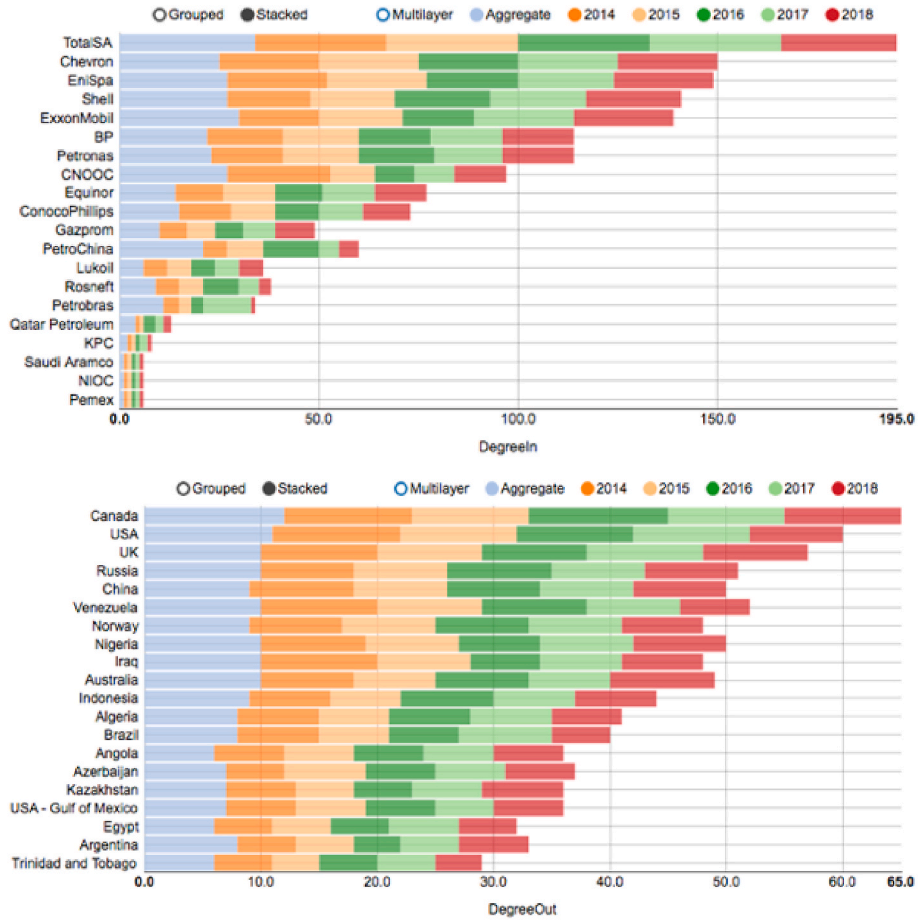

Fig. 3a and b. Total Hydrocarbons, Network Degree: 2014–2018: a) Degree in: number of countries in which each firm is extracting oil and gas; b) Degree out: number of firms extracting oil and gas from each country.

3.3. Network correlation company type

The interlayer Spearman correlation measures the assortativity of multiplex networks: while positive correlations indicate that nodes that are highly active in one layer are also highly active in a corresponding layer (assortativity), negative correlations indicate that nodes that are highly active in one layer have lower activity in another layer (disassortativity). Because *companies* are exclusive to particular layers (ExxonMobil, for example, only appears in the IOC/Big Oil layer), this metric indicates the likelihood of *countries* in which either IOCs, NOCs, or Hybrids are active for *companies from another category* to be active in those countries as well. Countries in which NOCs are extracting oil are slightly disassortative with Hybrid companies, and more disassortative with IOCs; by contrast hybrid and IOCs tend to be active in the same countries. Moreover, both these trends have become more pronounced since 2014: NOCs are becoming slightly more disassortative (indicated by increasingly negative correlations) with Hybrid and IOCs, Hybrids and IOCS are becoming more assortative (indicated by increasingly positive correlations; Table 4). In this context, countries that have NOCs, for example, were less likely to have IOCs or Hybrids operating there than in other countries, and this trend increased over time from 2014 to 2018. We can also infer growing cooperation and coordination among IOCs and Hybrid companies.

3.4. Clusters/community detection

Community detection using the Louvain method to determine modularity shows clusters (groups of producers operating in the same countries/groups of countries with the same companies) within networks for oil, gas, and total hydrocarbons. As expected, the level of modularity is lowest for total hydrocarbons (0.066) because it aggregates oil and gas extraction, which are often concentrated in different regions. This contrasts with the somewhat higher modularity of oil (0.104) and even higher modularity of gas (0.269) networks. The higher modularity of gas networks can be interpreted to correspond at least partially to the continental limits of pipelines, which geographically constrain the countries to which natural gas can exported, whereas there is a global market for more readily transportable oil (although the emergence of the global market for Liquified Natural Gas (LNG) is impacting this traditional delineation between these two forms of energy).

In 2017 in the total hydrocarbon network, BP, Rosneft, Gazprom, Lukoil, Venezuela's PDVSA, and Basra Oil Company can be seen to form a cluster, as did Chevron, Sinopec and PetroChina, as well as Shell, Exxon, and Nigeria's NNPC (Fig. 8). In the gas network (with all years represented), other clusters emerged, including ExxonMobil, ConocoPhillips, Petrobras and Qatar Petroleum, as well as another including Gazprom, TotalSA, ADNOC and Basra Oil Company (Fig. 9a). The latter group, joined by PDVSA, also formed a cluster in the oil network, as did Shell, ExxonMobil, Petrobras and NNPC (Fig. 9b).

Further structure is evident in the clusters within NOCs, Hybrids and IOCs modeled as separate networks. Each NOC (Fig. 10a) constituted its own community, reinforcing the picture of NOCs acting independently with respect to extraction. Since all the NOCs are also OPEC members (except Malaysia's Petronas, which is depicted in the hybrid group), their seeming isolation was countered by the community formed by OPEC. In the hybrid network, three clusters of two companies each emerge (Fig. 10b): 1) Lukoil and Gazprom, 2) PetroChina and Sinopec,

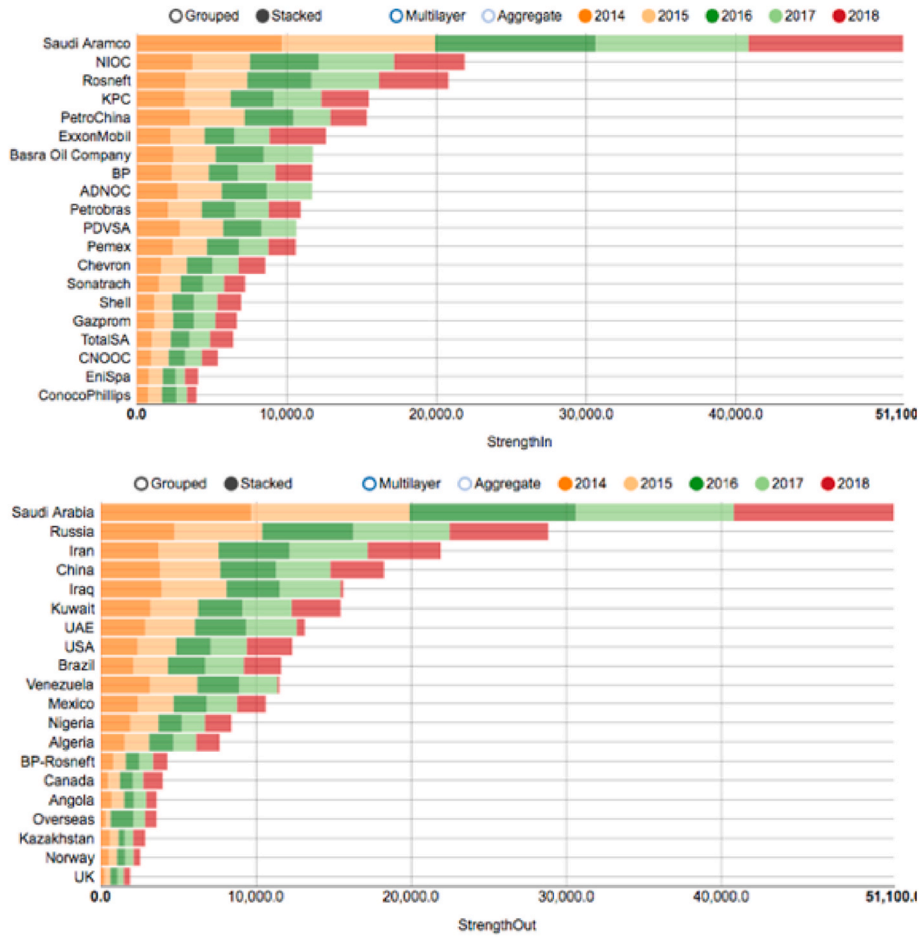

Fig. 4a and b. Crude Oil and Other Liquids, Node Strength: 2014–2018. a) Strength in: total flow of crude oil and other liquids to each company from all countries listed in the dataset by year; b) Strength out: total flows from each country to the Top 26 companies.

and 3) Petrobras and Equinor. While the first two can be seen to reflect ownership by their respective states, Russia and China, the third indicates similarities between Petrobras and Equinor, both having major offshore and deepwater resources in their respective home countries of Brazil and Norway, as well as a presence in the Gulf of Mexico and offshore Nigeria. However, while Equinor is present in Brazil, Petrobras is not active in Norwegian waters.

While IOCs are active in many of the same countries, they also specialize in specific regions. In the gas network there are two clusters: 1) ExxonMobil and ConocoPhillips formed a cluster (both operating in Canada, Norway, Indonesia, Russia, UK, USA, Qatar, Libya, Malaysia, and Timor-Leste) and 2) TotalSA and BP (both operating in Algeria, Angola, Argentina, Azerbaijan, Bolivia, Oman, Trinidad and Tobago, Gabon, Yemen, Italy and France) (Fig. 11a). In the oil network TotalSA and Shell (both European Big Oil companies operating in Norway, Oman, Brazil, Denmark, Gabon, and Brunei) formed the only cluster (Fig. 11b).

4. Discussion

These results illustrate the scope and complexity of the global oil and gas extraction network, providing a window into its historical roots and the continuing influence of this history on the network's organization, interdependence, and the profound inequities inherent in the distribution of its benefits and harms. Global production networks (GPNs) can be seen as "contested fields" in which actors struggle over the construction of economic relationships, governance structures, institutional rules and norms, and discursive frames" (Levy, 2008: 4). Moreover, "each of the actors in the global economy is involved in *both* cooperation and collaboration on the one hand *and* in conflict and competition on the other" (Coe et al., 2008:288; Dicken, 2004:13). In this discussion we make several observations regarding the oil and gas networks depicted above, highlighting instances of cooperation and conflict among key actors. As the climate crisis intensifies, we further note that the type of collaboration and the type of rivalry inherent in the global oil and gas extraction network is becoming increasingly toxic, increasingly powerful, and increasingly untenable.

Network Interdependence and Strategic Alliances: It is important to note that the growing interdependence among these companies and the active joining of forces through "rivalrous collaborations" and shifting alliances can be difficult to discern solely through an analysis of the countries in which they operate. However, they are evident when mapping several types of linked ownership structures, including joint ventures through subsidiaries and equity holdings, operating and service contracts, and strategic cooperation agreements (de Graaff, 2011). These relationships powerfully connect nodes within the global network; their occurrences are documented in the data sources compiled to construct the GOGEN. Joint ventures and equity holdings are widespread, but inconsistently documented in annual reporting and other public data sources. Even with reporting gaps, however, we found 1180 of some 2050 records (58%) at the subnational level in this dataset indicate some type of joint ownership with other companies, most commonly in the form of joint ventures through equity holdings. These relationships illustrate the increasing risks of extracting oil and gas from ever more remote locations, the merging of operations, and the shared motive among different producers to ensure that their investments and

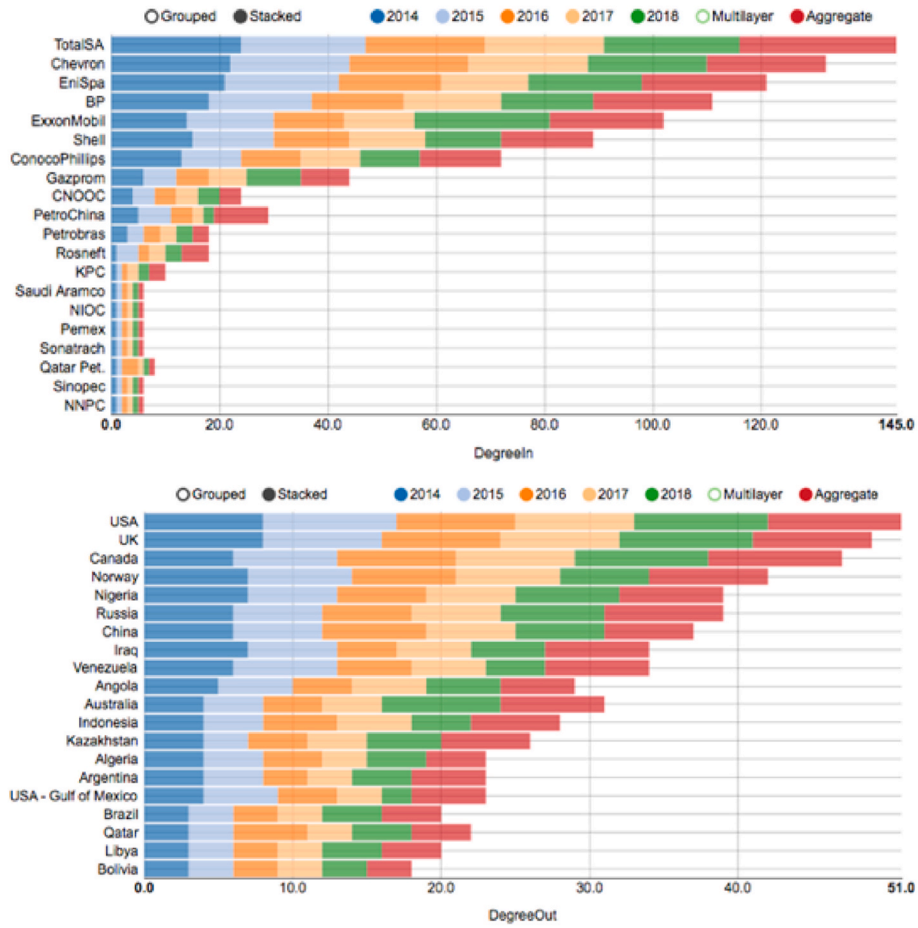

Fig. 5a and b. Liquids, Node Degree: 2014–2018. a) Degree in: number of countries in which each firm is extracting crude oil and other liquids; b) Degree out: number of firms extracting crude oil and other liquids from each country.

operations continue unimpeded.

The modest degree of modularity/clustering we find in the oil and gas extraction network illustrates the between-group alliances among IOCs, Hybrids, and NOCs that concentrate in particular regions. In contrast to the IOCs, the largest NOCs, with their mandates determined by national governments, tend to focus primarily on extraction within their home countries. This is evident in the contrast between Figs. 10 and 11: Fig. 10 shows that the NOCs and their home countries form distinct clusters; even when those clusters include other countries, no other NOC is present that in country (for example Qatar Petroleum is also present in Dem. Rep. Congo, Brazil and Canada; but no other NOC is there; likewise KPC is the only NOC with a presence in Norway). By contrast, Fig. 11 shows the extensive set of resource-holding countries in which Big Oil extracted oil and gas from 2014 to 2018.

The emerging LNG market represents another example in which there is profound interdependence among a complex set of industry actors. As Bridge and Bradshaw note: "Where, when, and how (in a contractual sense) LNG moves worldwide depends on how a diverse group of economic agents—including international oil companies, state-owned oil and gas producers, sovereign governments, municipal utilities, shipping companies, and gas traders—are sustained in relation with one another," highlighting not only the interdependencies within this network but also "how network territoriality is constitutive of markets rather than merely responsive to them" (Bridge and Bradshaw, 2017: 224, 215). They further note the prevalence of joint venture agreements among NOC and IOCs, as well as the role of the Hybrid company PetroChina (a portion of which is publicly traded) in transnational upstream investment:

Transnational investments in the liquefaction phase of the LNG production network are dominated by joint-venture arrangements between national oil companies and the IOCs—notably Shell, BP, Total, Exxon Mobil, Chevron, and ENI. A number of state oil and gas firms, such as Malaysia's Petronas and PetroChina (both partners in proposed LNG export plants in British Columbia, for example), are also active as transnational investors in upstream LNG (Bridge and Bradshaw, 2017: 231).

Key Network Nodes: A subtle but defining characteristic of this particular network model is how the largest oil-extracting countries are represented through the formal relationships they have with the companies that are directly engaged in the extraction within their borders. The U.S. and Russia produce more total hydrocarbons than Saudi Arabia, yet there are profound differences in the contribution these three countries make to the network of the top 26 global oil and gas companies. More crude oil was extracted per day in the United States than Saudi Arabia in 2018 (EIA, 2024). However, as this analysis illustrates, U.S. output (primarily through hydraulic fracturing) was split among many different companies (primarily IOCs). By contrast, Saudi Arabia's output is channeled to its NOC Saudi Aramco, the company which continues to extract the most hydrocarbons per year; its longstanding and pivotal role in the global oil market is attributable to its massive, relatively accessible reserves and modest domestic demand (Mitchell, 2013). Russia's Hybrid companies Rosneft and Gazprom similarly dominated natural gas extraction during this period. Again, although the U.S. also produces more natural gas per year than Russia, its output is also divided among many different producers.

The transition of Saudi Aramco from NOC to a Hybrid company with a small amount of publicly traded shares occurred with an initial public offering (IPO) in 2019, further illustrating the dynamic nature of the oil

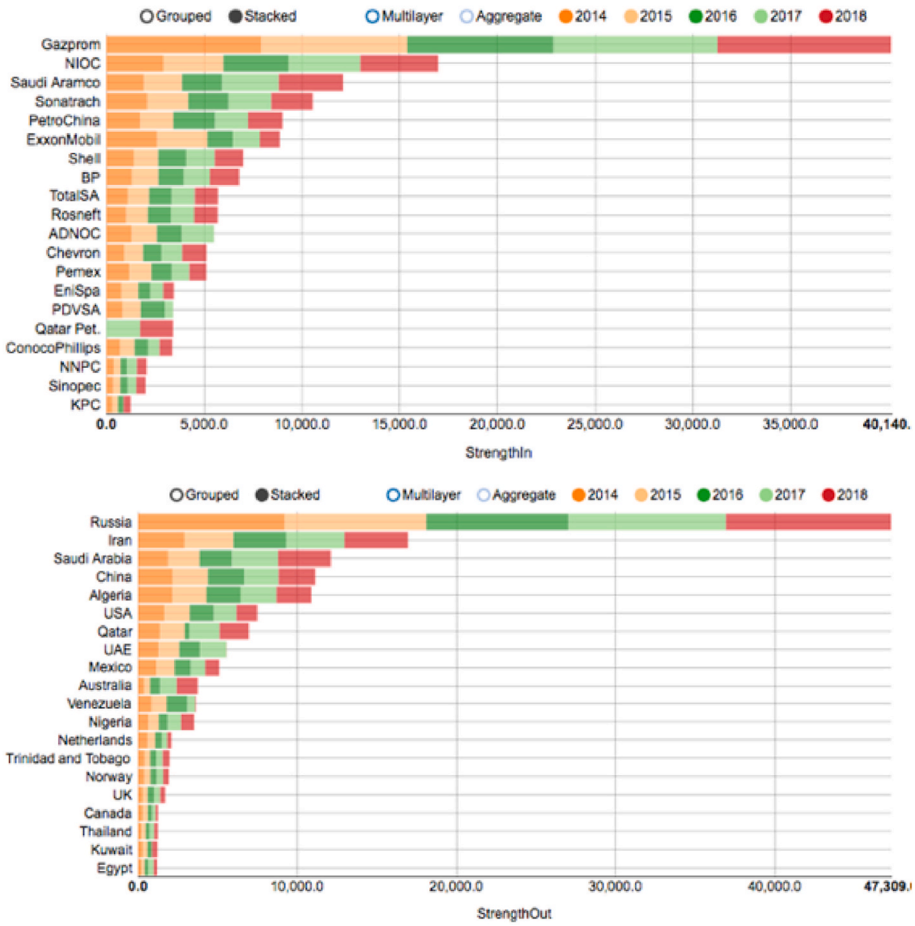

Fig. 6a and b. Natural Gas, Node Strength: 2014–2018. a) Strength In: total flow of crude oil and other liquids to each company from all countries listed in dataset by year. b) Strength Out: total flows from each country to the 26 companies included in this dataset.

and gas industry. Its pre-tax income in 2023 was $247 billion USD, establishing it as the most profitable publicly-traded company in the world; Apple was a distant second at $114 billion USD (Mancini, 2023). Both the company's profitability and its transition from NOC to Hybrid is also emblematic of the concentration of power in the hands of specific actors embedded in the global network of public and private oil and gas extractors, whose ongoing influence and authority rests on the continuation of the global carbon economy.

The Role of Big Oil: Another defining characteristic of the network is that IOCs extract hydrocarbons from more countries than any other type of producer, although their output is smaller than the top NOCs and Hybrid companies. This arrangement may be seen as a direct legacy of centuries of colonial rule. The three IOCs headquartered in the U.S (ExxonMobil, Chevron, ConocoPhillips) and four in Europe (BP, Royal Dutch Shell, TotalSA, EniSpa) also play critical roles as producers and suppliers in their home countries, exerting hidden influence on political processes to maintain their position, particularly as efforts to transition to renewable energy intensify. As evidenced by the number of countries in which they operate, and the profusion of joint ventures and extraction sharing agreements, each IOC has deep ties to other producers around the world, effectively forming a subterranean coalition with formidable influence in virtually every country in the world. The ongoing presence of IOCs in resource-rich regions around the world, now predicated on the negotiation of ground rent with resource-holding states (Bridge, 2008) is unsustainable, benefiting both from governments willing to negotiate and wars when resource-holding states do not wish to take part in such negotiations. While the Production Gap report is a vital tool to highlight the gap between national plans and the extraction occurring within their borders, it does not directly address the role of transnational IOCs in global extraction. This actually creates another gap – overlooking the vested interests of these powerful companies in preventing, subverting, delaying, and obstructing a transition (the ultimate aim of which is absolutely necessary to avoid a global climate catastrophe) that at the same time will lead to their demise.

Countries Without IOCs and a Potential Role for NOCs in Facilitating a Just Transition: In light of the above observations, Germany and Denmark (two European countries that do not serve as headquarters for Big Oil companies) can be seen as structurally motivated to legislate more ambitious national decarbonization targets. These two countries are unique in that they have "maintained active support of renewable energy development since the 1970s" (McBryan, 2009: 335). Denmark offers a compelling example of an oil and gas producing country with a NOC that has been able to transform into a renewable energy company. Danish Oil and Natural Gas (DONG) was founded in 1972 as Dansk Naturgas A/S to manage Denmark's considerable offshore oil and gas resources in the North Sea. In 2008, moved by public coal opposition and the upcoming climate conference in Denmark the following year, the company made the critical and risky decision to adopt the "85/15 vision," flipping within a decade from 85% fossil fuel-based electricity and heat production to 85% renewable energy (Clowes, 2020; Huchler, 2023). Now the largest offshore wind farm company in the world, the renamed Ørsted is a Hybrid, publicly-listed company on the Nasdaq stock market, with the Danish government owning a majority share (50.1%) until at least 2025. In 2020 Denmark announced a legally binding end date for the extraction of oil and gas by 2050 aligned with goal of carbon neutrality in the same year (Madsen et al., 2023) and in 2021, along with Costa Rica, Denmark co-launched the international Beyond Oil and Gas Alliance (BOGA) of governments and stakeholders

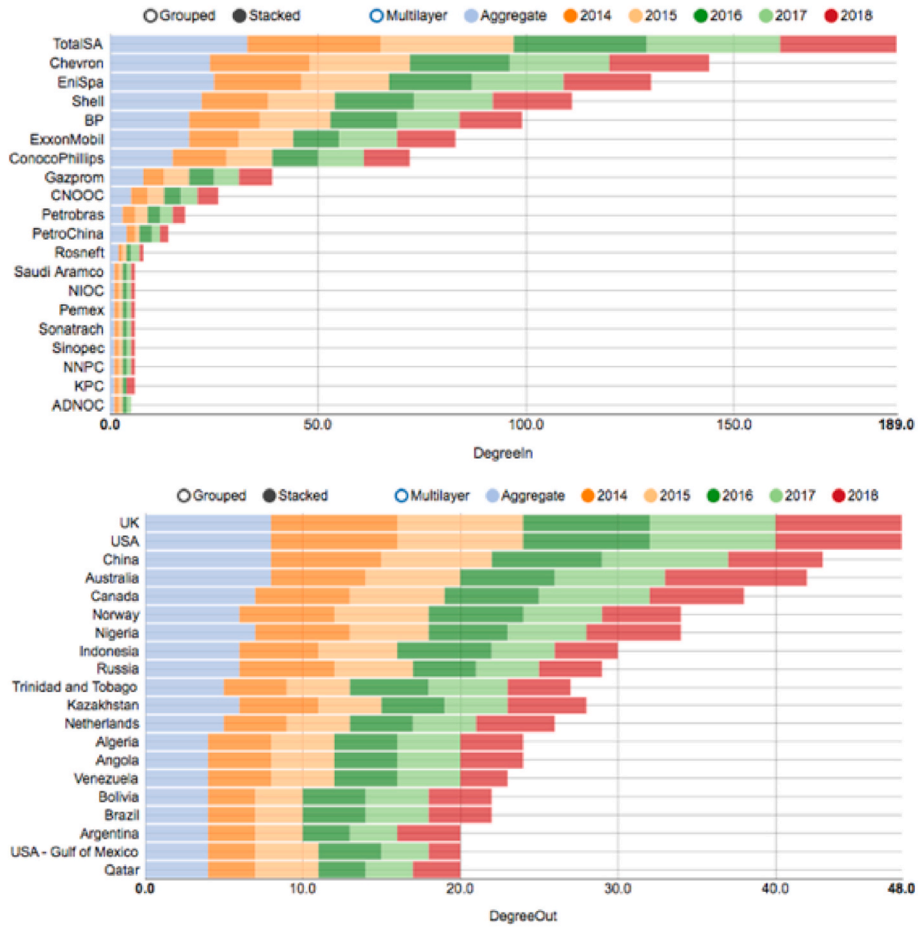

Fig. 7a and b. Natural Gas, Node Degree: 2014–2018. a) Degree In: number of countries in which each firm is extracting crude oil and other liquids; b) Degree Out: number of firms extracting crude oil and other liquids from each country.

Table 4
Interlayer Spearman correlation.

Metric	Network	NOC-Hybrid	NOC-BigOil	Hybrid-IOC
Spearman Correlation	Tot HC: 2018	−0.226	−0.237	0.290
	Tot HC: 2014	−0.177	−0.228	0.176
Spearman Correlation	Liquids: 2018	−0.195	−0.15	0.148
	Liquids: 2014	−0.145	−0.166	0.123
Spearman Correlation	Natural Gas: 2018	−0.188	−0.208	0.092
	Natural Gas: 2014	−0.186	−0.220	0.049

working towards the managed phaseout of oil and gas production. The role of the UAE, home of ADNOC, the fourth most extractive oil and gas company in 2018 (Table 2), as host of COP28 in 2023 highlights the changing role some major oil and gas producing states with NOCs are playing in global climate negotiations, and their attempt to diversify into the arena of renewable energy, while at the same time obstructing any legally binding action for a full phaseout.

Identifying Transnational Industry-State Collusion: Garrod and Olczak (2018) note an important distinction between explicit and tacit collusion under competition law: while explicit collusion involves a group of firms in direct communication, "usually with the intention of coordinating their actions to raise profits above competitive level," tacit collusion involves firms coordinating their actions without such direct communication (2018:3). As this study has shown, an intricate global network of joint ventures, equity holdings and cooperative agreements effectively 'sits under' the network of companies extracting oil and gas from specific countries, about which there is relatively sparse public information. Hybrids and IOCs are increasingly extracting oil and gas from the same countries, typically countries without NOCs. This is explained partially by partnerships among IOCs and Hybrid companies (most vividly illustrated by BP's 20% ownership stake in Russia's Rosneft during the period from 2014 to 2018). The notable exception is Iraq, which has seen multiple Big Oil (Europe and the US) and Hybrid (Russia and China) companies step in since the Iraq War. Figs. 2–7 in this study depict the network analysis of the extractive locations and the state and corporate actors involved in global oil and gas production, while Figs. 8–11 depict ongoing cooperation and competition within this network.

The extent of both tacit and explicit collusion among oil and gas extracting companies and nation-states (that is, globally among IOCs, NOCs, and Hybrids and the governments of extractor countries) has been greatly understudied; moreover, such collusion applies not only to setting oil and gas prices (Aune et al., 2010), and but also to the policymaking arena, where tacit collusion serves to obstruct global climate policies aimed at a fossil fuel phaseout.

5. Conclusions and policy implications

As this analysis illustrates, the global fossil fuel system consists of a complex network of powerful, strategically aligned corporate and state actors that have a vested interest in ongoing fossil fuel extraction. Given the interconnectedness, global reach, and combined power of the major private, hybrid, and state oil and gas producers, effective international governance of oil and gas extraction is essential to achieve a just

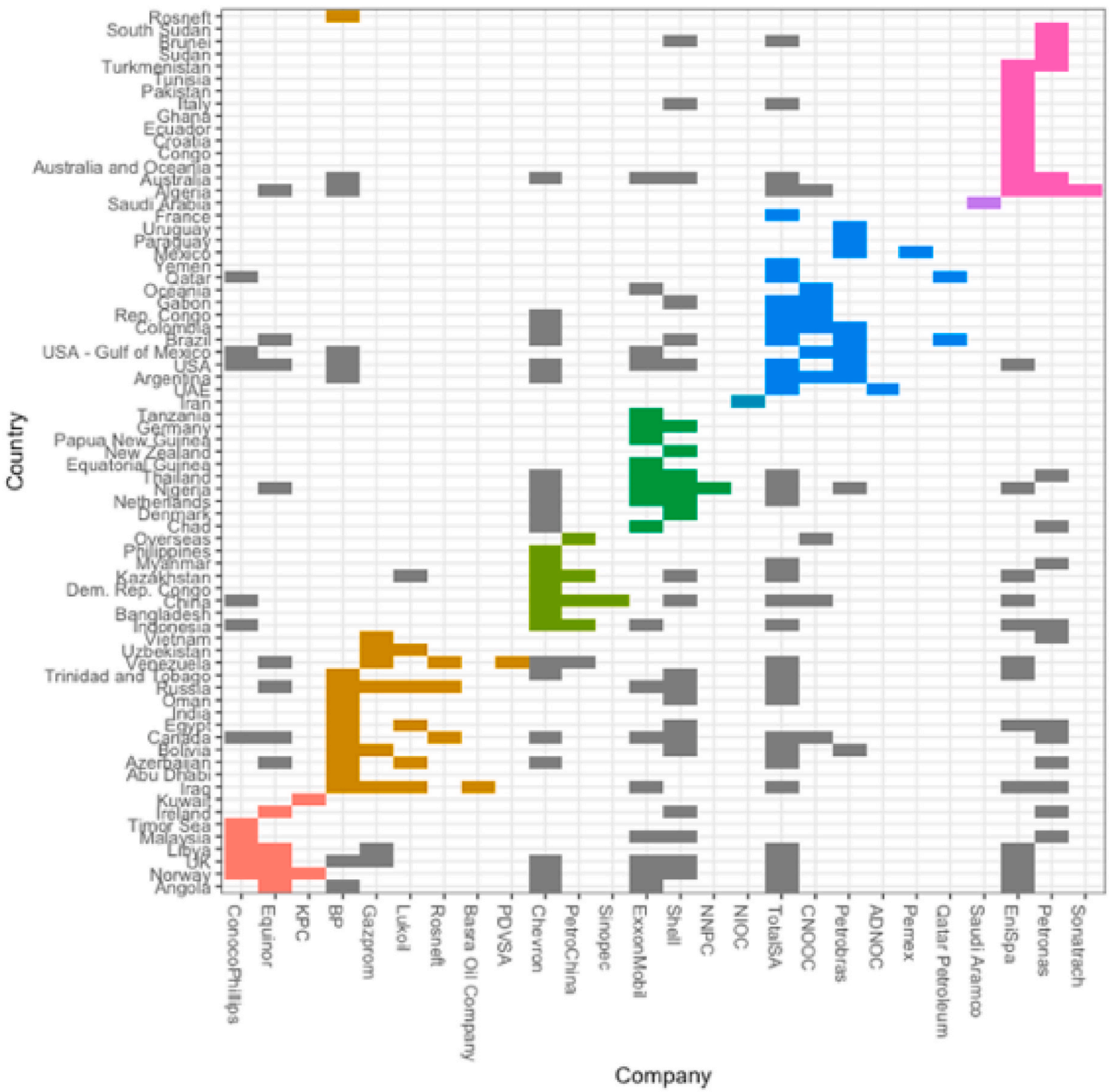

Fig. 8. Communities in the total hydrocarbons network in 2017 for all 26 companies. BP's 20% equity holding (prior to the Ukraine war) in Rosneft is represented separately, with Rosneft appearing in the country category to signify this relationship.

transition (Jasanoff, 2018) away from fossil fuels.

Developing an effective global strategy to mitigate climate change will require alignment of policies that simultaneously address all elements of this powerful and opaque transnational system. Although Denmark's experience with its NOC and the BOGA Alliance offers a hopeful example, for the most part neither national nor global governance structures have as yet been able to effectively regulate transnational oil and gas interests for a managed phaseout of extraction with a clear timeline. Current global strategies to mitigate climate change focus on national-level commitments to reduce carbon emissions rather than industry commitments to curb extraction. The goal of reducing warming to 1.5 °C is unlikely to be met unless and until there is a planned and coordinated phaseout of fossil fuels.

In addition to shedding light on some of the hidden dimensions of the oil and gas extraction network, this study highlights that an important precursor for effective governance of a phaseout is open data spanning the entire global network for the full life cycle of fossil fuels. While transparent data is not the only factor delaying effective international carbon governance, it is an essential component for such governance. For one, it would – in some cases for the first time – clearly and openly document the activities of oil and gas interests responsible for extracting these resources in all the countries in which they operate. This in turn would foster a deeper public understanding of the complex realities involved, and the role of these interests in influencing both climate policies and global oil and gas prices.

The oil and gas industry is driven by both *competition* for access to resources and markets and *cooperation* in the form of joint ventures, equity holdings, production control, and price influencing. During the study period from 2014 to 2018, the relationships among oil producing companies and governing bodies might also be characterized as *transnational industry-state collusion* to delay and obstruct the unfolding energy transition for as long as possible (Carroll, 2021; McKie, 2021). Although there have been many grassroots efforts to develop publicly available data of fossil fuel extraction at the company level, there are structural reasons why comprehensive datasets do not already exist in useable form. The Global Oil and Gas Extraction Network represents one step in this ongoing effort.

Key areas for further development of the GOGEN include: a) the addition of monetary values corresponding to sales of the volumes of oil and gas extracted from each country; b) the addition and analyses of

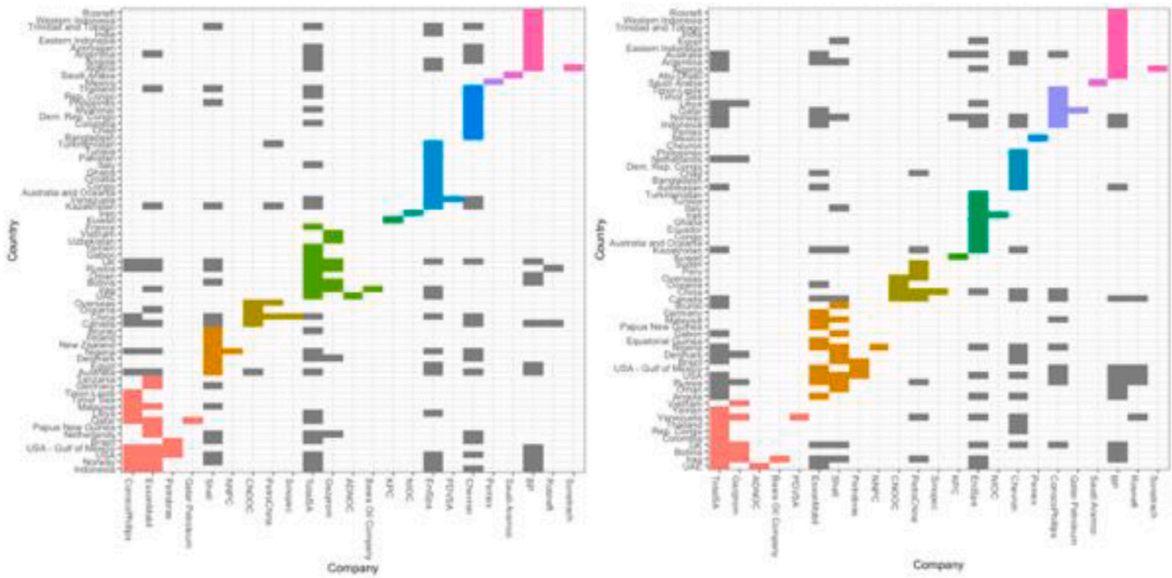

Fig. 9. Gas (a-left) and liquids (b-right) for all companies across 2014–2018. The gas network displays more modularity (0.269) than the crude oil network (0.104).

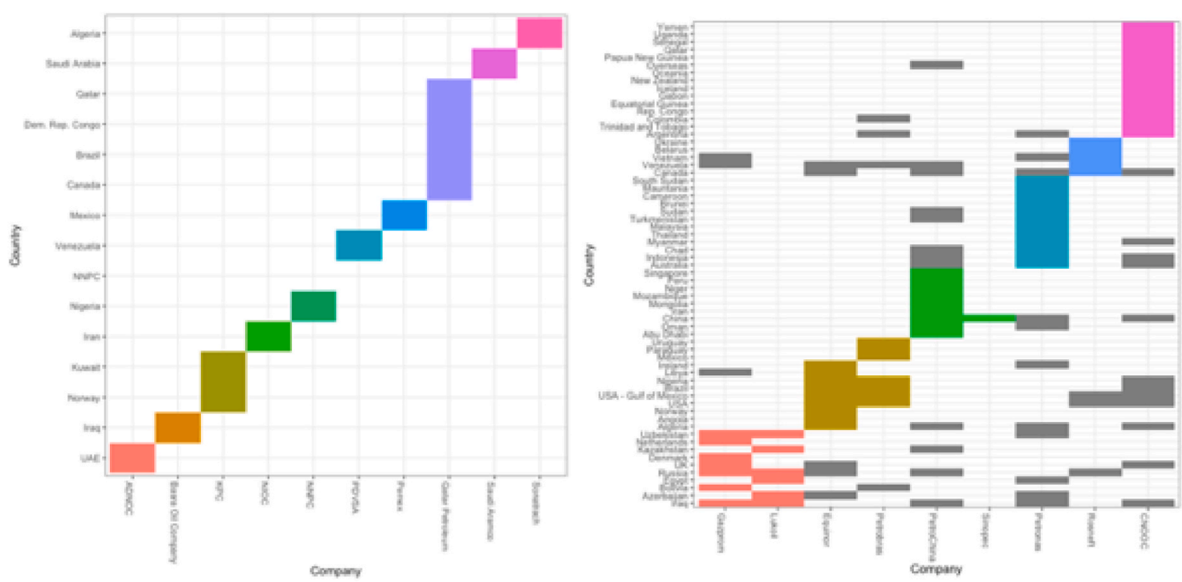

Fig. 10. Communities for NOCs (excluding Petronas, a-left) and Hybrids + Petronas (b-right) extraction for total hydrocarbons.

mid- and downstream operations (including refining, petrochemicals, sales, taxes paid to state entities, and carbon emissions); c) the use of currently proprietorial field-level industry data; and d) an extension of the temporal range back to 2000 and forward to 2023, with annual updates thereafter. In conjunction with traditional national-level energy data, bottom-up datasets documenting activities and impacts of oil and gas extraction, as well as ecoregions, agriculture, water scarcity and other spatial layers, a wider dataset could be also used to track trans-boundary social-ecological harms and embodied energy injustices (Healy et al., 2019) traceable to complex fossil fuel extraction processes that are inherently global in both reach and impact. Moreover, insights obtained from such analysis can be leveraged to inform more effective global governance of the increasingly urgent phaseout of fossil fuels.

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CRediT authorship contribution statement

Sonya Ahamed: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Gillian L. Galford:** Writing – review & editing, Supervision. **Bindu Panikkar:** Writing – review & editing. **Donna Rizzo:** Writing – review & editing, Methodology. **Jennie C. Stephens:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

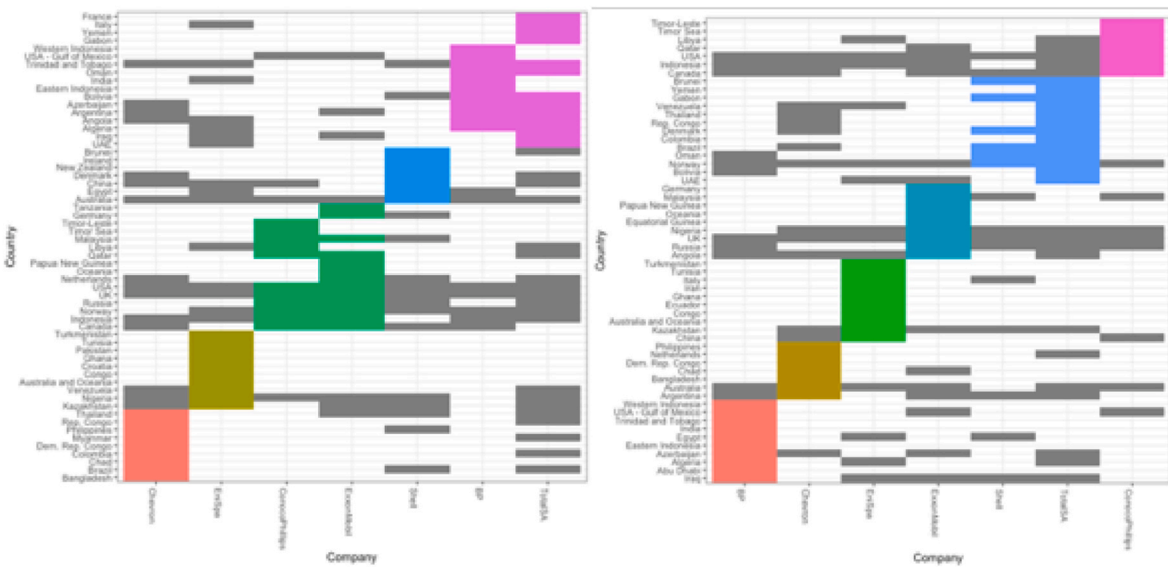

Fig. 11. Communities for gas (a-left) and crude oil b-(right) extraction of Big Oil.

Data availability

Data Available online on open data repository and as supplementary information

Appendix A. Data limitations and uncertainties

Compilation of non-standardized data from widely disparate sources posed a number of challenges, ranging from non-standard reporting requirements, multiple units and classifications, varying levels of specificity, and outright data gaps.

- There is no single format for US SEC Form 20-F filings for foreign companies; some companies collapsed SEC filings into their annual reports. Where separate, SEC filings and annual reports occasionally listed different amounts for production (e.g. EniSpa); in such cases data from the more recent publication was used.
- Equinor reported production of total hydrocarbons only and therefore is not represented in the separate gas and oil networks.
- Equinor and ConocoPhillips were the only two companies whose annual reports: a) consistently listed the percentage of their equity holdings in all partner-operated fields, b) named the partner company acting as operator for that field, and c) provided the amount extracted from that location.
- Subnational location data was often scattered throughout 'operational highlights' narratives rather than in table form. Varying amounts of detail were provided for specific projects, countries or locations; actual volumes extracted were not always given and when they were, they were inconsistently separated into oil and gas or amalgamated. Similarly, data for geographic locations variously reported details and quantities at the project, formation, play, state, regional, or basin level.
- Virtually all companies report only net, rather than gross, production totals, thereby not providing a clear picture of how much energy is consumed in the production process.
- There are numerous data gaps: many companies do not provide readily accessible data on the location of their operations within countries, and/or do not report quantities. Petronas, the state-owned Malaysian oil and gas company which conducts major exploration and production operations abroad, for example, lists the countries in which it extracts oil and gas in its annual reports, but does not provide quantities. PetroChina and CNOOC aggregate volumes extracted abroad under the category "Overseas."
- Data gaps in some cases are due to deliberate lack of transparency: in Europe, Asia, Africa, and South America, Shell lists an "Other" category comprised of "countries where 2018 production was lower than 7300 thousand barrels *or where specific disclosures are prohibited*" (Royal Dutch Shell, 2019: 48).
- Geographic regions are aggregated and referred to differently (i.e. Australia and Oceania, Oceania, Middle East, Middle East and North Africa).
- Production from equity-accounted entities/subsidiaries is not handled consistently: some include equity holdings as part of total production, others list it separately (in a few cases it was not clear which was the case). Non-operating partners in co-ventures are generally not listed. BPs 20% equity holding of Rosneft: In the Annual Report BP reports production by country for equity holdings of Rosneft as "Rosneft (Russia, Canada, Venezuela, Vietnam)."
- National Iranian Oil Company figures rely on the BP Statistical Review for the country of Iran, although Shell and CNOOC/PetroChina, Rosneft have listed operations and/or exploration of opportunities there, so these totals should be considered an approximation.
- As alluded to above, several companies indicated they extracted oil or gas from a specific country but did not indicate the quantity in a given year; the table below provides an overview of the 13% of edges (375 of 2829 records) that fall into this category.

A1-Table 1
Description of records in the edge list used for network analysis that contained missing weights

Company	Number of records with missing weights	Countries in which company operated but weights are missing
Big Oil		
Chevron	42	Chad, China, Dem. Rep. Congo, Netherlands, Norway, Trinidad and Tobago
EniSpa	2	China, Venezuela
ExxonMobil	13	Indonesia, Iraq, Ireland, Papua New Guinea, Tanzania, Venezuela
TotalSA	63	Azerbaijan,
Hybrid		
Gazprom	31	Bolivia, Denmark, Iraq, Netherlands, UK, Uzbekistan, Venezuela, Vietnam
Rosneft	35	Belarus, Canada, Ukraine, USA, USA - Gulf of Mexico, Venezuela, Vietnam
CNOOC	44	Algeria, Argentina, Australia, Brazil, Canada, Colombia, Equatorial Guinea, Gabon, Iceland, Indonesia, Iraq, Myanmar New Zealand, Nigeria, Papua New Guinea Qatar, Rep. Congo, Senegal, Trinidad and, Tobago, Uganda, UK, USA, USA - Gulf of Mexico, Yemen
PetroChina	40	Abu Dhabi, Algeria, Australia, Canada, Indonesia, Iran, Kazakhstan, Mongolia, Mozambique, Niger, Oman, Peru, Russia, Singapore, Turkmenistan, Venezuela
Petrobras	11	Argentina, Bolivia, Colombia, Mexico, Nigeria, Paraguay, Uruguay, USA, USA - Gulf of Mexico, Venezuela
NOC		
Petronas	91	Algeria, Argentina, Australia, Azerbaijan, Brunei, Cameroon, Canada, Chad, China, Egypt, Indonesia, Iraq, Ireland, Malaysia, Mauritania, Myanmar, Oman, South Sudan, Sudan, Thailand, Turkmenistan, Uzbekistan, Vietnam
Qatar Petroleum	3	Brazil

Appendix B. Network Metrics

The following well-known network properties were used to analyze these networks (Barabási, 2016; M. Newman, 2010; M. E. J. Newman, 2006).

a. *Average degree*: $<k>$ the average number of links per node in the network, obtained by dividing the total number of links (m) in the network by the number of nodes N.
b. *Node strength, s*: The sum of weights attached to ties belonging to an individual node.
c. *Transitivity/clustering coefficient*: of the degree to which nodes in a graph tend to cluster together: Local clustering coefficient C_i for directed graphs,

$$C_i = \frac{\left|\left\{e_{jk} : v_j, v_k \in N_i, e_{jk} \in E\right\}\right|}{k_i(k_i - 1)}$$

where e_{jk} is the edge between vertices v_j and v_k for immediately connected vertices in neighborhood N_i with set of edges E in the full graph G with set of vertices V. The global clustering coefficient for networks is:

$$C = \frac{3 \times number\ of\ triangles}{number\ of\ all\ triplets}$$

d. *Interlayer Assortativity coefficient, r:* (Pearson correlation coefficient): the extent to which network nodes are linked to nodes with similar properties (often measured in terms of degree). In directed graphs, in-assortativity and out-assortativity measure the likelihood of nodes to link to others with similar in- and out-degrees as they have. Assortativity, r, ranges between −1 (fully disassortative), 0 (non assortative), and 1 (fully assortative)

$$r = \frac{\sum_{jk} jk\left(e_{jk} - q_j q_k\right)}{\sigma_q^2}$$

where q_k is the distribution of the remaining degree (that is, the number of edges leaving the node, excluding the edge that connects the current pair), e_{jk} is the joint probability distribution of the remaining degrees of the two vertices, and σ is a scaling term.

e. *Spearman Correlation,* $\rho_{\alpha\beta}$: the strength s_α of countries in one layer compared to their strength s_β in other layers

$$\rho_{\alpha\beta}(pq) = 1 - \frac{6\sum_{i=1}^{N}\left[r_\alpha^{(i)}(p) - r_\beta^{(i)}(q)\right]}{N\left(N^2 - 1\right)}$$

where $p; q$ = ingoing, outgoing, or total strength, and $r_\alpha^{(i)}(p)$ is the rank of node i in layer α. Strong positive correlations indicate countries that are very active in one layer are also very active in another layer and, conversely, strong negative correlations indicate countries active in one layer are much less active in another layer (Baggio et al., 2016).

f. *Multiplexity, g(v)*: is the shortest path among nodes in a connected graph such that the number of edges or the number of weights (for weighted graphs) is minimized for every pair of nodes. Betweenness centrality for each node is the number of shortest paths that pass through that node.

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where σ_{st} is the total number of shortest paths from vertex *s* to vertex *t* and $\sigma_{st}(v)$ is the number of such paths that intersect *v*.

g. *Modularity, Q:* is defined as a scalar value between −1 and 1 measuring the density of links inside communities compared to links between communities(Girvan and Newman, 2002; M. E. J. Newman, 2006). In the case of weighted networks it is defined as

$$Q = \frac{1}{2m} \sum_{ij} \left[A_{ij-} \frac{k_i k_j}{2m} \right] \delta(c_i, c_j)$$

and implemented in igraph and muxviz using the Louvain method for finding community structure by multi-level optimization of modularity(Blondel et al., 2008).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2024.114103.

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