Exposing the Environmental Costs of Offshore Oil:
Greenhouse Gas Emissions, Oil Slicks, and Flaring

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April 23, 2025

Abstract

Despite the need to reduce greenhouse gas (GHG) emissions to mitigate climate change, the global offshore oil and gas (O&G) industry continues to develop around the world. While the number of offshore structures is relatively stable, the industry is poised for rapid growth and is increasing its use of Floating Storage and Offloading, Floating Production Storage and Offloading, Floating Liquefied Natural Gas, and Floating Storage Regasification Unit vessels (collectively FxOs) to extract, produce, and store oil and gas. These FxOs and traditional O&G fixed infrastructure pose significant risks to both immediate and long-term climate and conservation goals, through a combination of oil pollution, methane release, and natural gas flaring, as well as the net GHG footprint required to operate and maintain these structures and vessels. In this report, we assess the offshore O&G Industry's environmental footprint. We highlight 20 offshore oil facilities that stood out in satellite imagery for the frequency and extent of oil pollution events. These structures were responsible for 228 oil slicks, amounting to at least 295,000 gallons over a 16 month interval from June 2023 to October 2024, with individual structures likely producing as many as 175 slicks during that period. Additionally, this paper begins to uncover the carbon footprint of the offshore oil industry, including CO_2 emissions associated with the transport of O&G at sea and quantifying frequency of methane flaring. We found that offshore oil facilities were visited at least 40K times by vessels, and these vessel visits were responsible for at least 9 million tons of CO_2 emissions in 2023. That same year, 23.1 BCM of methane were flared by offshore oil facilities, resulting in 58.7 million metric tons of CO_2e (CO_2 equivalent) emissions. The results of this analysis can be used by resource managers and environmental advocates to enforce marine protections and monitor progress towards meeting climate goals.

Glossary

Fixed Oil Infrastructure: stationary offshore oil infrastructure locations identified by Global Fishing Watch, detected using Sentinel-1 and Sentinel-2 imagery. The fixed oil infrastructure dataset does not differentiate between structure type (e.g. platforms, mooring buoys, terminals).

FLNG: Floating Liquefied Natural Gas vessel

FPSO: Floating Production Storage and Offloading vessel

FSO: Floating Storage and Offloading vessel

FSRU: Floating Storage Regasification Unit vessel

FxO: collectively refers to the vessels engaged in the production, storage, and offloading of oil and gas, which includes FLNG, FPSO, FSO, and FSRU.

Offshore Oil Facilities: a combined list of known FxO operating locations and fixed oil infrastructure identified by Global Fishing Watch.

Operating Locations (OL): locations where at least one FxO loitered for a minimum of 60 consecutive days, determined from AIS position.

Operating Period: a location and date range that an FxO loitered for at least 60 consecutive days, determined from AIS position.

All oil slick detections presented in this report are based on analysis of satellite imagery and have undergone human review. However, satellite imagery alone cannot determine the precise composition, concentration, or source of detected slicks. As such, these detections should not be interpreted as definitive evidence of pollution or illegal activity. Some slicks may originate from natural seeps, including those located near offshore infrastructure. All interpretations are made to the best of our ability using available data, and are intended to support transparency and further investigation, not to assign liability.

Introduction

Climate change is an immediate and severe threat to the planet. The UN Environment Programme Emissions Gap Report for 2024 [Ref] found that global emissions increased to an all-time high in 2023, despite the need to reduce emissions by 2030 to avoid climate change's worst impacts. Regardless of this need, the offshore oil and gas (O&G) industry continues to expand in response to rising demand. In 2015, offshore oil accounted for 30% of global oil production [Ref], and in 2022 and 2023, the offshore industry broke $100 billion in capital expenditures per year for the first time in a decade [Ref]. The offshore drilling market is projected to increase from an estimated $36.52 billion in 2023 to 74.94 billion by 2032 [Ref]. Oil companies claim that offshore oil is more environmentally sustainable than drilling on land due to the lower amount of greenhouse gasses emitted in production, including a reduction in methane emissions by one-third per barrel of oil produced [Ref]. However, new research suggests that methane emissions from offshore oil production are substantially higher than the original estimates [Ref, Ref, Ref].

Oil spills affect marine life by damaging sensitive species and ecosystems such as mangroves and coral reefs [Ref, Ref, Ref], forcing animals away from their normal habitat [Ref], and having decades long impacts on animals that rely on surfacing for air such as sea otters [Ref], as well as the downstream effects on birds and other animals that feed on the directly affected marine life. The Deepwater Horizon oil spill has been extensively studied, and it has had extremely adverse effects to the marine environment, as well as migratory birds [Ref]. That spill itself, which dumped 4 million barrels of oil into the Gulf of Mexico [Ref], affected an estimated 48% of the critically endangered Rice's whale habitat [Ref], whose population totals only around 100. In addition to rapid mortality of heavily oiled seabirds, lightly oiled seabirds migrate more slowly [Ref], which may have long term effects on reproductivity, and habitat degradation affects their ability to migrate for many years after a spill [Ref]. Damage to fisheries and loss of tourism as a result of the spill caused a loss of billions of dollars and jobs in the coastal states [Ref, Ref]. Catastrophic oil spills gain the most media attention; however, prolonged slow leaks also plague offshore infrastructure [Ref].

Although development of new static offshore oil facilities has not expanded significantly in the last few years [Ref], a rise in deepwater oil and gas exploration activity, in part driven by the depletion of onshore and near-shore wells, is driving exploration deeper out at sea. Deeper sea exploration requires particular types of vessel-like, moveable, floating oil platforms, including Floating Storage and Offloading (FSO), Floating Storage Production and Offloading (FPSO), Floating Liquefied Natural Gas (FLNG), and Floating Storage Regasification Unit (FSRU) vessels, which are the focus of this white paper, and we will refer to these collectively as FxOs. The push toward deepwater oil and gas exploration is expected to cause a jump in the market for FPSOs in particular by over 150% over the next decade [Ref, Ref], as they act essentially as moveable oil production platforms suitable for deepwater development. In addition to being able to operate in deeper water, FPSOs have the advantages of being easily moveable to other operating locations, and being cheaper and faster to stand up than a traditional oil platform [Ref, Ref, Ref].

The FPSO sector is estimated to have produced 38 million metric tons of CO_2 in 2023 [Ref], the rough equivalent of 8.3 million cars [Ref]. FPSOs contribute to approximately 4% of global gas flaring with a few dozen super-flaring FPSOs making up most of that [Ref, Ref]. Due to limited ground measurements, offshore methane flaring and especially venting has been difficult to monitor, though use of satellite imagery is starting to paint a picture [Ref].

Additionally, FxOs have had many safety concerns and violations. Catastrophic failures have occurred on FPSOs as a result of aging infrastructure, technical failure, and human error. This includes the Trinity Spirit explosion off the coast of Nigeria, which left 7 people dead and dumped 60,000 barrels (nearly 2.52 million gallons) of oil into the ocean [Ref] and the Cidade de Sao Mateus explosion in February 2016 off the coast of Brazil, which killed 9 people and injured many more [Ref]. While the major explosions generate the most news coverage, several other explosions or fires aboard FxOs have resulted in fatalities and oil spills [Ref], and have been involved in many small to medium volume oil spills [e.g. Ref, Ref, Ref, Ref, Ref, Ref], with offloading equipment being a major source of such spills [Ref]. Even after the end of life of an FPSO, scrapyard casualties are at least in the dozens from FPSOs in the shipbreaking process [Ref, Ref, Ref].

In recent years, efforts have been made to decarbonize FPSOs and reduce their environmental footprints [Ref, Ref] by incorporating carbon capture, reinjection, and including green energy (including wind and tide) to power production. For example, the Brazilian oil company Petrobras has committed billions of dollars toward reducing GHG produced by their FPSOs, including a reduction in methane by 70% by 2030 [Ref]. The first carbon capture system to be installed in an FPSO, a joint venture between Yinson Production and Azule Energy on FPSO Agogo, is currently in the works [Ref]. The GHGs emitted by FPSOs themselves are not the only environmental harm caused by FPSOs. A large portion of emissions associated with FPSOs and offshore oil in general are related to tankers transporting oil, as well as the travel of other service vessels needed for operation.

Natural gas has been marketed as a cleaner alternative to oil due to lower CO_2 emissions produced in combustion [Ref, Ref]. However, this is not the only environmental factor to weigh. For example, the liquefaction, storage, and regasification of natural gas requires significant amounts of energy [Ref, Ref], and the net GHG footprint of LNG has been estimated to be 33% higher than that of coal [Ref]. Additionally, methane leaks have been detected surrounding LNG terminals and other O&G facilities [Ref], and although methane does not live in the atmosphere for as long as CO_2, its warming power is over 80 times higher [Ref, Ref].

In addition to producing climate warming greenhouse gasses (GHG) and oil spills, the offshore oil and gas industry is responsible for ecosystem disruption caused by increased vessel traffic [Ref, Ref], seismic blasting [Ref], and the discharge of toxic hydraulic fluids into the water [Ref]. Activity at sea, particularly on the high seas, is less regulated and harder to track than in national jurisdictions. Therefore, illegal and environmentally harmful activity may take place when operators believe that they are not being monitored. Because of the known harm caused by oil spills and bilge dumping, and the difficulty of monitoring such behaviors out at sea, remote sensing has gained popularity in identifying spills [Ref, Ref, Ref]. Combined with Automatic Identification System (AIS) vessel location information, efforts are also being made at pinpointing sources [Ref].

There is a vital need to increase transparency of offshore O&G development, to ensure that countries are making progress towards their climate goals, and to highlight instances where they fail, or actively seek not, to make progress. Increased transparency will strengthen enforcement efforts, allowing countries to hold polluters, and the companies which own them, to account. SkyTruth, with support from our partners at Global Fishing Watch (GFW), is releasing new data to illustrate the extent of the offshore oil industry's impact on the climate and ocean.

In this paper, we discuss the development of a few data products that are freely available upon request, including: 1) A comprehensive list of offshore oil facilities, 2) FxO periods and locations of operation, 3) Voyage level emissions for vessels associated with offshore oil facilities, and 4) Aggregated flaring for offshore oil facilities. Additionally, we present some initial results highlighting the environmental impacts of the offshore oil industry. In particular, we address trends in development, oil slicks production, and methane flaring from offshore oil facilities, as well as CO_2 emissions associated with oil and gas storage and transportation.

Offshore Oil Facilities

FxO Operating Locations

Before it was possible to investigate the impacts of offshore O&G facilities, we needed to confirm their locations; no public global dataset exists. The desired outcome of this analysis was to confidently identify all operational FxOs between January 1, 2013 and October 29, 2024 and to produce a comprehensive inventory of their operating locations during this period. Operating locations are defined as offshore locations where FxOs lingered consistently for more than 60 days and where they could have feasibly been engaged in oil and gas exploration or production. The process for identifying FxOs begins by creating a list of International Maritime Organization (IMO) numbers that are associated with ships that are currently, or previously, identified as FxOs. IMO numbers are unique to every vessel, and do not change, unlike Maritime Mobile Service Identity (MMSI) numbers which may change during ownership transfers. IMO numbers, along with additional metadata, are collected from the IMO registry, a query of national registry data provided by GFW, and manual investigation of vessel tracking websites.

Once these lists of IMO numbers are compiled, we join them together based on the IMO to consolidate information in instances where different sources contain unique information, and format this into a single dataset. Metadata which we preserve in this dataset includes: the IMO number, MMSI number, vessel callsign, build data, current owner, and current status. We assign confidence levels to each IMO based on our ability to pair it with a MMSI number. There are several IMOs recorded in our list which have no MMSI numbers, there are several reasons this may occur. First, the vessel has been registered but is still under construction and therefore has not used MMSI. Second, the vessel has been decommissioned, lost, or destroyed. However, in some cases a manual review of additional sources, including Marine Traffic and Marine Vessel Traffic, was required to identify valid MMSI.

In our initial list we identified 621 unique IMOs; of these 351 had MMSI data recorded in our source. For the remaining 270 we were able to manually identify a further 92 valid MMSI. We combine these manually identified IMO/MMSI pairs with the data in our FxO Identity master list to create a single dataset of vessels for which it is possible to identify AIS tracks.

GFW houses several terabytes of AIS location data for vessels from 2012-present [Ref, Ref]. The frequency of AIS broadcasts from vessels depends on the type of AIS device and how it is moving (moving faster or changing course results in more transmissions), and can range from 2 seconds to three minutes. However, only a small fraction of messages are recorded by commercial providers, and, depending on the region of the world, the time between positions can range from less than a minute to several hours. Using these broadcasts, operating locations for FxOs are interpolated by finding the average location each day when there are any AIS tracks in the GFW table. We used GFW's processing pipeline to eliminate faulty positions, which result from noise in the radio frequency transmission, bad timestamps, or multiple vessels using the same identifier.

Per IMO regulations, vessels exceeding 500 gt must always report location via AIS, and non-fishing vessels exceeding 300 gt must operate AIS on all international voyages [Ref], except under circumstances where the safety of the crew may be at risk, such as traveling through conflict zones or areas of known piracy [Ref]. However, vessels also tend to shut off AIS when engaging in illegal activity, such as trading sanctioned oil [Ref]. FxOs generally have gross tonnage on the order of tens to hundreds of thousands, and therefore, any long FxO gaps in AIS location are considered behaviors of interest. Gaps in FxO AIS data are calculated based on the number of days when the FxO did not report its location via AIS for an entire day.

Operating locations are defined here as locations where FxOs have remained stationary for a period of time. Clustering is performed with a density-based spatial clustering of applications with noise (DBSCAN) algorithm on the daily location data, with the min_samples criteria set to 60 (i.e. the FxO was in the vicinity of the cluster center for at least 60 days), to create a set of potential operating locations. Because FxOs are sometimes converted from tankers, we only include daily AIS tracks during the periods that the vessel was operating as an FxO. This list is reduced by implementing a second criterion that the FxO remains at the potential operating location for at least 60 consecutive days. The full list of potential operating locations was hand labeled to create the final list of 326 operating locations, as well as identify anchorages, shipyards, ports, and terminals.

Fixed Oil Infrastructure

Global Fishing Watch (GFW) has developed an offshore infrastructure dataset using Synthetic Aperture Radar and optical imagery to identify and classify offshore infrastructure [Ref]. Our dataset of stationary offshore oil facilities combines the list we generated of 326 FxO operating locations with GFW's dataset of 24,506 fixed oil infrastructure locations. GFW's data is derived from a detection model which uses Sentinel-1 imagery to identify fixed infrastructure at sea coupled with a Sentinel-2 based model which classifies the type of infrastructure [Ref]. Currently, the GFW infrastructure table does not differentiate between types of oil facilities and structures, but some of the types that are captured include platforms, mooring buoys, onshore and offshore terminals, and occasionally non-oil related structures like ports and anchorages. Manual imagery review resulted in discarding some of the non-oil structures (for example, when an abnormally large number of vessels visited a facility and it turned out to be a shipping port).

Offshore Oil Facility Development

Our offshore oil facilities dataset includes "FxO operating location" and "fixed oil infrastructure", see Figure 1. All GFW-identified offshore infrastructure which is not separately identified as an FxO operating location in the FxO dataset is labelled with the structure_id from the GFW table in the infra_number column.

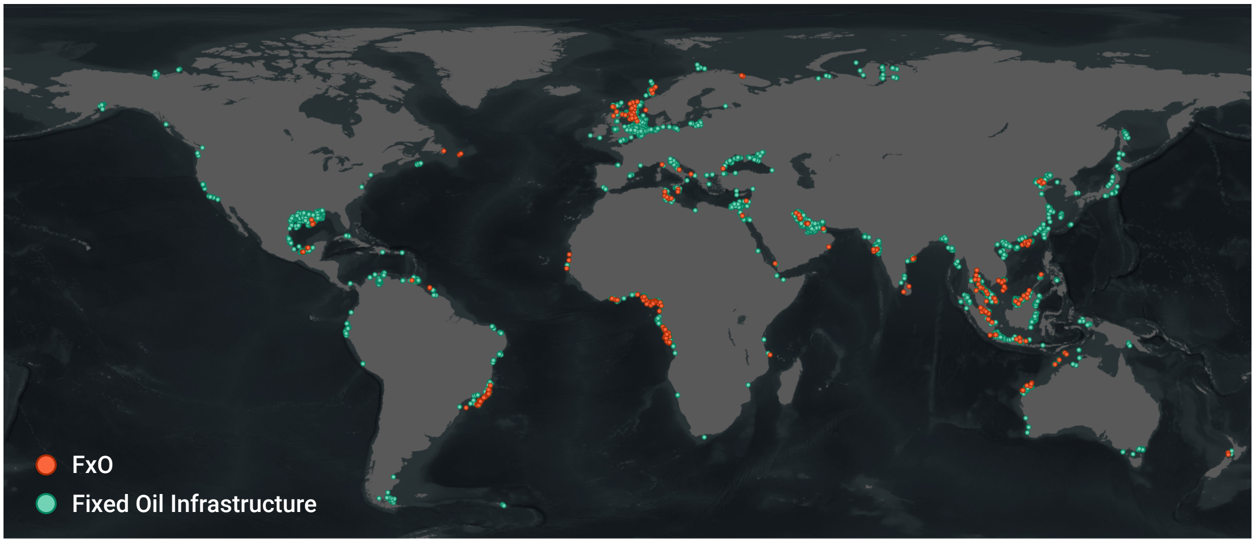


Figure 1: Infrastructure locations. GFW fixed oil infrastructure in green (24,506 locations), FxO operating locations in orange (326 locations).

Additionally, an operating periods dataset is generated, which includes the dates and durations of each FxO at each operating location they visit. This is determined from AIS location as times when the FxO is within 500 m of the operating location. An operating period ends when the vessel tracks suggest that it moves away from the operating location, and a new operating period begins when it returns to the operating location or moves to another one.

The number of FSOs has been steadily increasing since the 1970's, with FPSOs seeing a sharp increase starting in the late 1990's. FSOs peaked in the 2010's, followed by a slight decline, while FPSOs development continues to rise, see Figure 2. The cost of a new build FxO is substantially higher than the cost of adding production equipment to an existing tanker. Beginning in the late 1970's, and becoming more common in the early 2000's, tankers were converted into FxOs, with 110 being converted into FPSOs and 141 being converted into FSOs as indicated by vessel records from the IMO Registry.

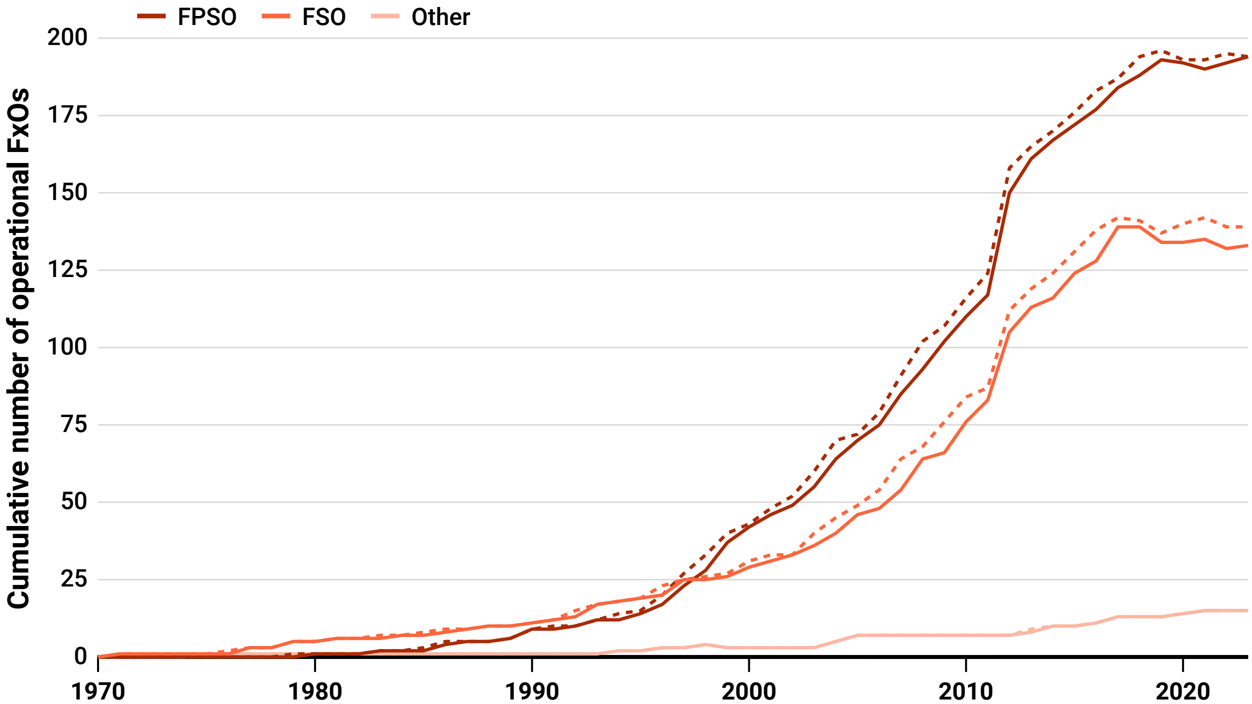


Figure 2: Number of FxOs (unique IMOs in each year); dashed lines include FxOs that have been converted from tankers (and a few FSO to FPSO conversions). The "other" category includes FxOs whose geartype does not include FSO or FPSO, and are listed as various other geartypes such as semi-submersible, bulk carrier, gas processing unit, and offshore support vessel. Many of the FxOs have since been decommissioned or destroyed, and if there is last_timestamp metadata associated, this is used as the approximate decommission date.

In total, 301 FxOs, including 184 FPSOs and 102 FSOs, have known operating locations. For these FxOs, we have identified 326 likely operating locations, 200 of which are visited by FPSOs, and 111 by FSOs, see Table 1. The median operating period of an FPSO is 988 days, which is 3.5 times that of FSOs. Additionally, we identified 16 vessels categorized as 'offshore support vessel' or 'gas processing vessel', which have been labeled as 'other', and also have long operating periods.

	OLs	Operating periods	OL days	% of days operating	Med operating period (days)
FPSO	200	453	2432	56	321
FSO	111	342	1721	45	93
OTHER	16	24	2070	46	723

Table 1: Operating location statistics for different types of FxOs: OLs - number of operating locations, Operating periods - number of operating periods (periods of at least 60 consecutive days during which the FxO remained at an operating location), OL days - average number of operating days per vessel, % of days operating - percentage of vessel's lifetime spent operating, med operating period - median duration (in days) of one operation.

The number of operating FxOs is shown below, see Figure 3, for the period of 2013-2023. The number of operating FPSOs increased between 2013 and 2019 and then plateaus. The reason for this plateau is unconfirmed, though one possibility is the uncertainty in the oil industry during the Covid-19 pandemic [Ref]. Due to projections of increased demand for FPSOs [Ref, Ref, Ref], we expect the number of operating FPSOs to begin increasing again in the next few years.

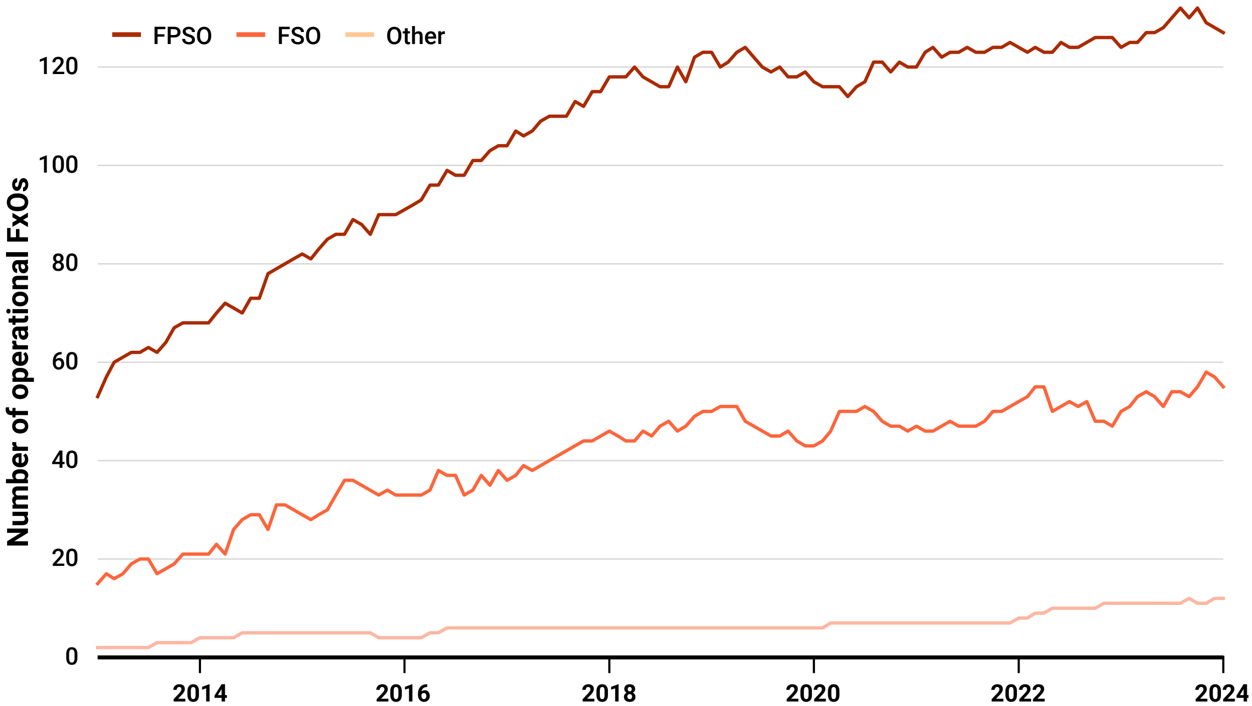


Figure 3: Number of FxOs at an operating location in each month.

Emissions associated with FxOs span all stages of the vessels' lifecycles, including emissions produced by ship building, drilling, production, storage, transportation, and shipbreaking. This analysis is limited to emissions associated with storage and transportation of oil and gas, not the total lifecycle footprint of FxOs. It is assumed that the storage of oil and gas on FxOs can be approximated similarly to oil and gas tankers. In 2023, the emissions associated with FxO chemical storage were estimated to be 1.5 million metric tons CO_2, see Figure 4. This is a relatively small fraction of the total GHG emissions associated with FxOs, which is said to be dominated by methane flaring from a few super flaring FPSOs [Ref].

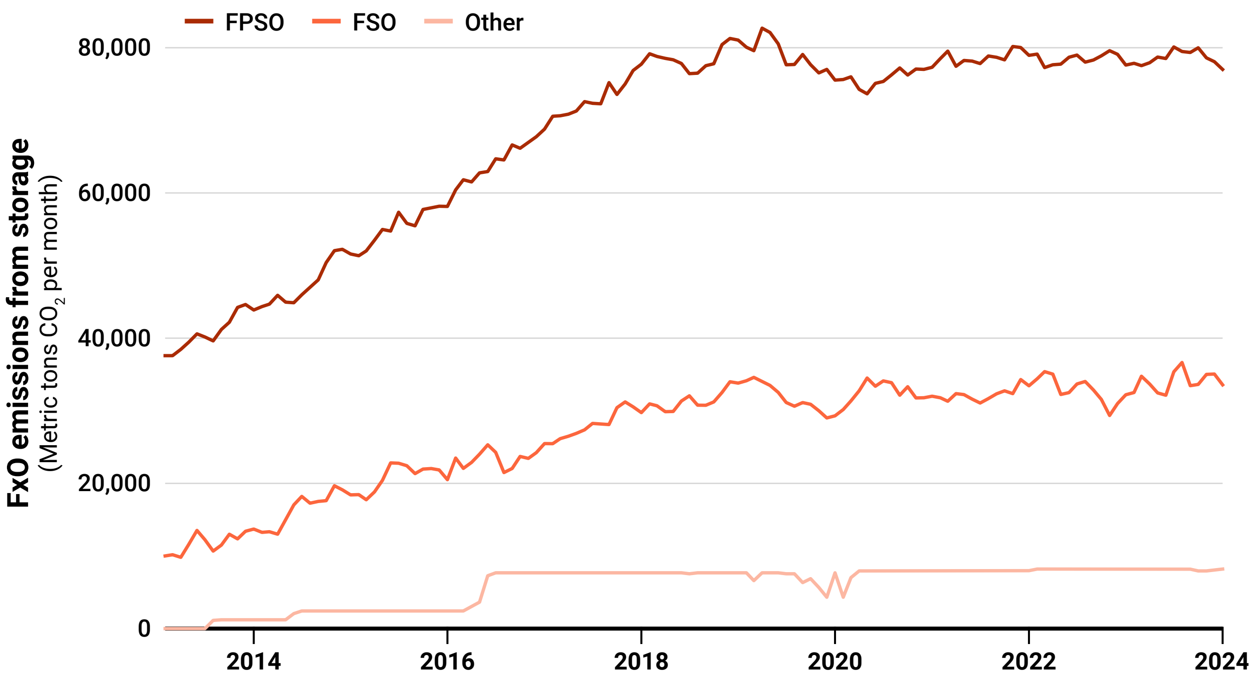


Figure 4: CO_2 emissions associated with chemical storage from FSOs and FPSOs operating in each year.

We have mapped 24,506 unique fixed oil infrastructure locations throughout the ocean. The amount of fixed oil infrastructure peaked in 2020 and has been declining since then. Because available fixed oil infrastructure data does not distinguish between different types of oil facilities or structures, it is unclear from this data alone how many of these are oil platforms versus on- and offloading terminals, see Figure 5. However, a similar trend is shown in the amount of flaring infrastructure (Figure 6), described more in the Flaring Activities section, leading us to believe that the decrease is because there are now fewer platforms producing oil and gas than in 2020.

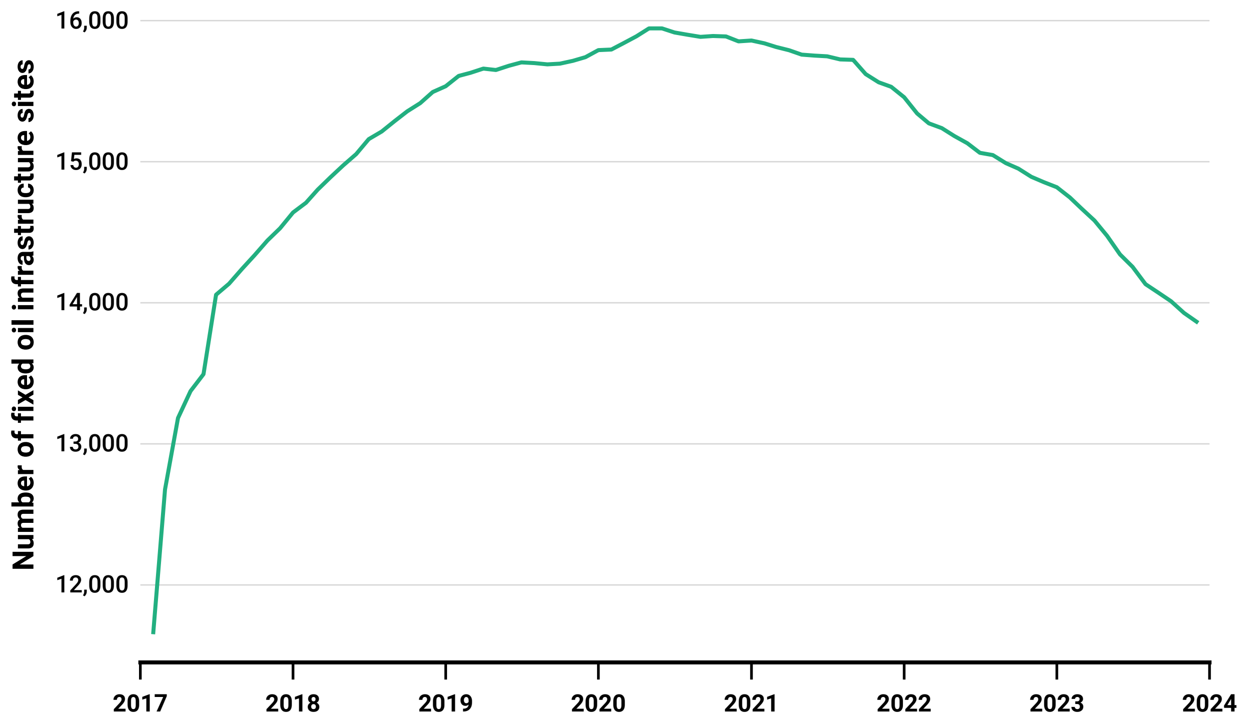


Figure 5: Number of existing fixed oil infrastructure locations in each year.

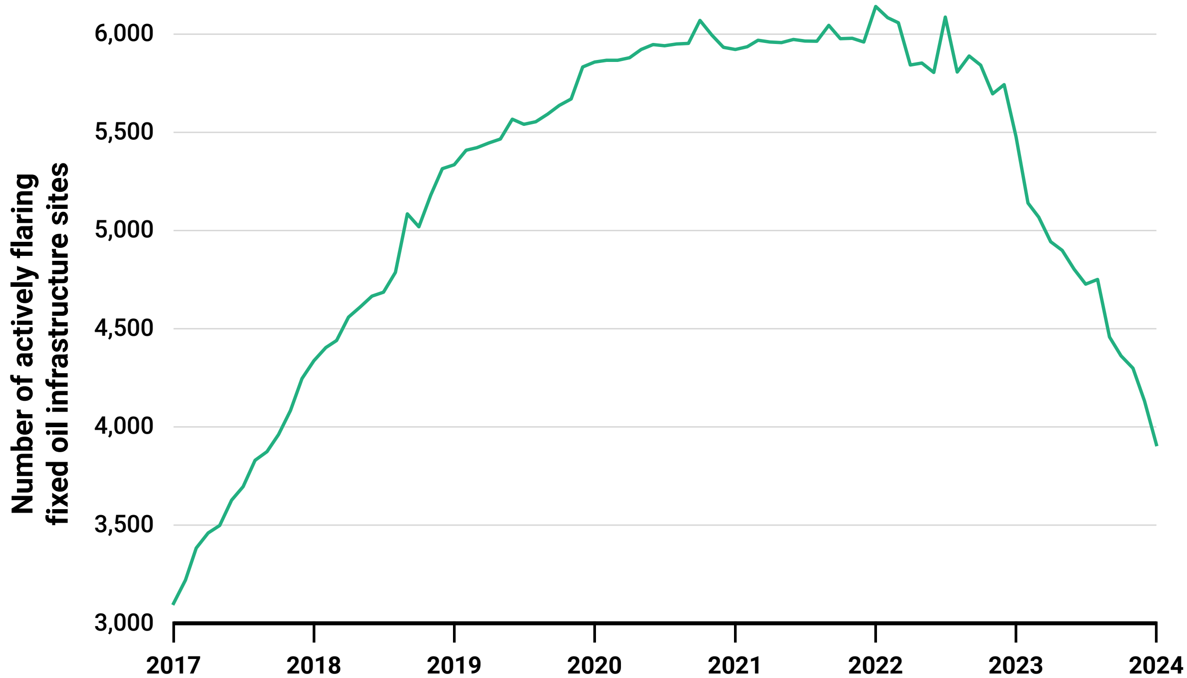


Figure 6: Number of actively flaring fixed oil infrastructure locations in each month.

Oil pollution

A major risk related to offshore oil development is the potential for oil slicks. These slicks, which can result from accidental spills, operational discharges, or equipment malfunctions, pose significant threats to coastal communities and marine ecosystems. SkyTruth's Cerulean model detects the presence of oil slicks on the water from Sentinel-1 imagery [Ref], see Figure 7. This dataset allows for regular monitoring and observation for FxO operating locations and other stationary oil infrastructure. Additional information about the methods, assumptions, and important caveats about satellite-based detection and measurement of oil slicks are detailed by the Cerulean documentation [Ref].

Obtaining oil slick volume estimates on a large scale is an important, yet elusive area of research. Satellite imagery is relatively good for estimating slick area; however, thickness and oil concentrations are much harder to pin down [Ref]. The thickness of a slick at the time of detection is related to the amount of time between the slick's occurrence and its detection; a new slick will be narrower and deeper, whereas a slick that occurred a few days prior will have spread but not be as thick [Ref]. In addition to the age of the slick, wind and current patterns [Ref], and the contents of the mixture affect its shape and persistence [Ref]. Many of the slicks identified by Cerulean are from bilge dumping [Ref], which is an intentional release of bilge water (dirty, oily mixture of varying oil concentration accumulated in a vessel's hull [Ref]) into the ocean. This analysis uses Sentinel-1 SAR imagery, which measures the roughness of the water surface [Ref]. The roughness is dampened by the presence of any oil [Ref], and is not sensitive to the thickness of oil. Our volume estimates for each slick were calculated assuming a conservative average minimum thickness of 1 μm [Ref], and the actual volume is likely substantially higher, particularly if the detection is a few days after the leak.

The initial analysis of the top likely polluting FxO operating locations and fixed oil infrastructure was conducted by identifying all Cerulean detected slicks within 500m of offshore oil facilities. FxO operating locations were first ranked based on the percentage of Sentinel-1 images which contained a Cerulean detected slick. Slicks were then manually reviewed to remove any which were mis-attributed to an FxO and cleaned to remove any portion of the detected slick which was unassociated with the source. Sources were then re-ranked as needed based on the removal of any slicks.

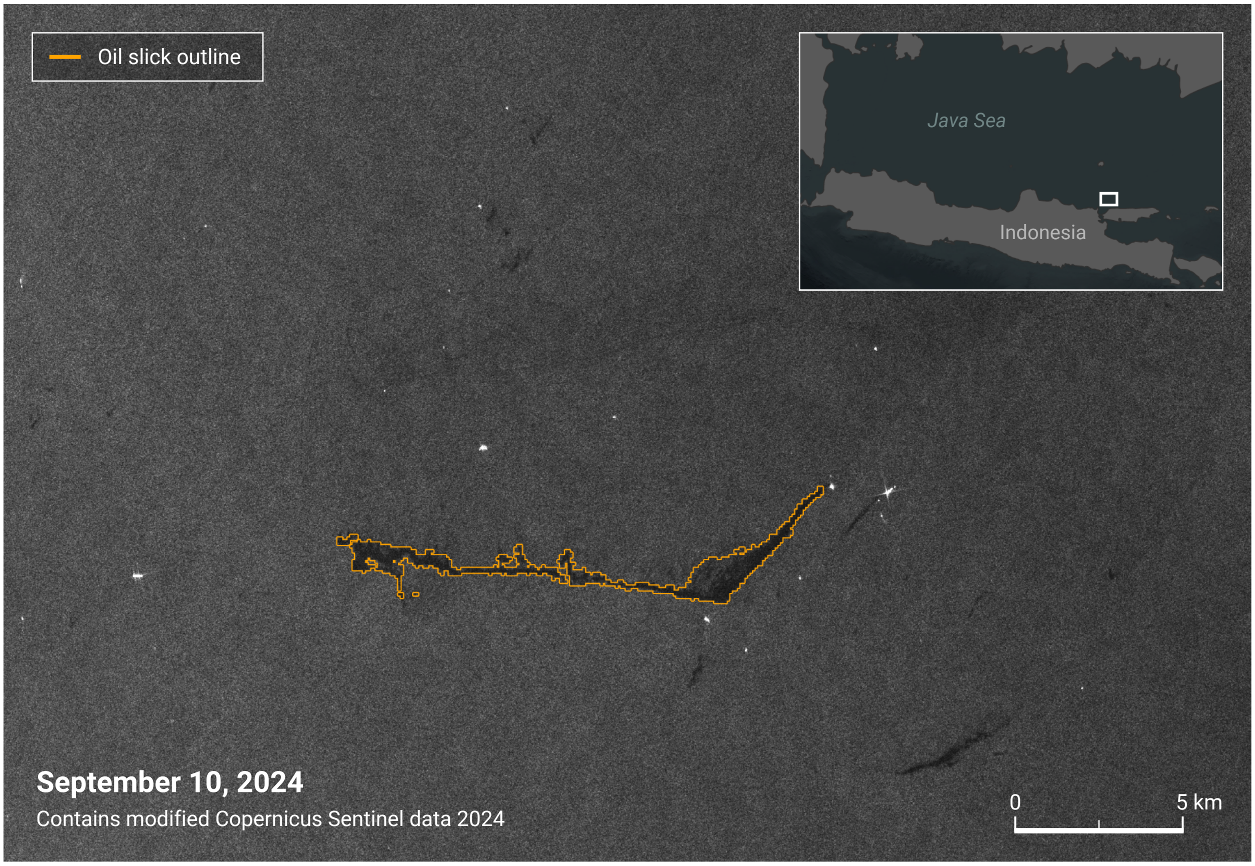
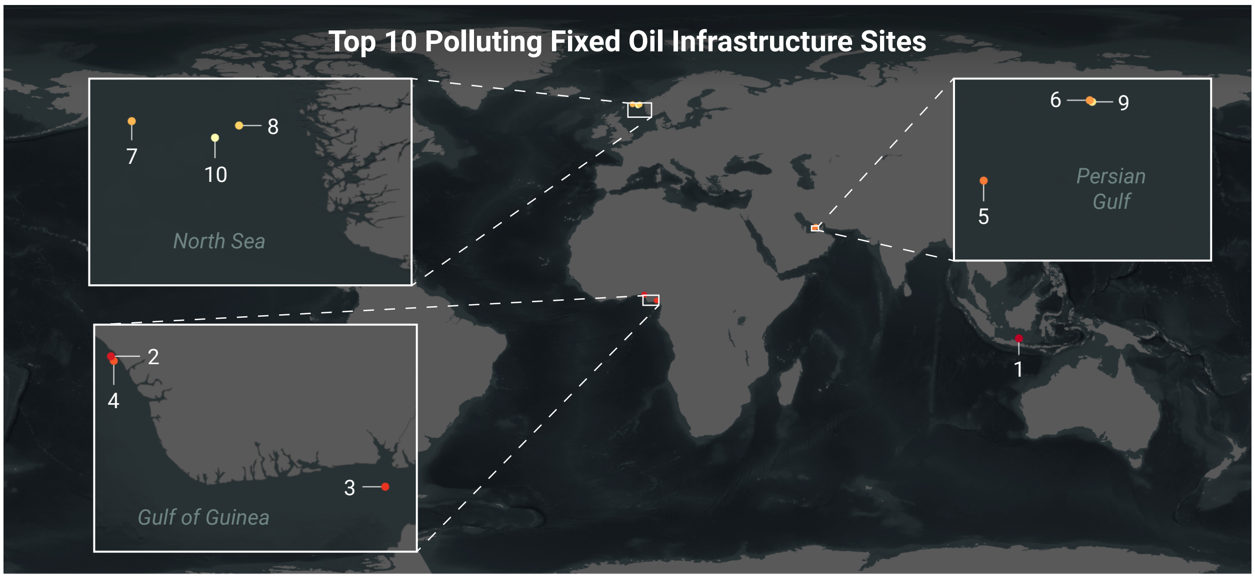


Figure 7: An oil slick detected by Cerulean (orange) from a Sentinel-1 image collected on 2024/09/10. The slick is associated with fixed oil infrastructure [Ref].

The comparatively large number of fixed oil infrastructure sites (>24,000 as compared to 326 FxO operating locations) was a barrier to a full review of all Cerulean detected slicks. To create the list of top likely polluting fixed oil infrastructure, the 50 locations with the greatest number of detected slicks were identified, and these slicks were reviewed manually to verify the source attribution and discard false slick detections. Locations were then ranked based on the percentage of Sentinel-1 images which contained a Cerulean detected slick, and then manually reviewed again to remove portions of slicks which were mis-attributed to a given source. Notably, the review and cleaning of slick detections did not include steps to add missed slicks, or missed portions of slicks, to the dataset; this may contribute to some instances where slicks appear to have spurious edges as a result of missed segments of a slick. From this analysis, the top likely polluting FxO operating locations and fixed oil infrastructure, as defined by the percentage of scenes where a slick was visible, are identified for date range of 2023/06/01 to 2024/10/09.

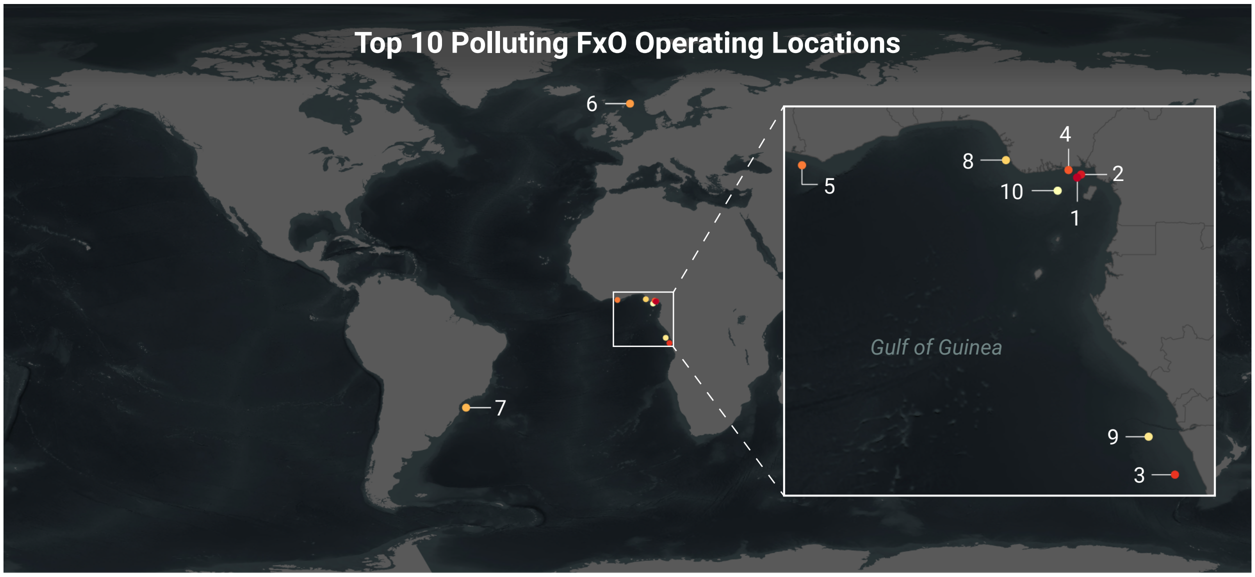
Over the 16 month period from June 2023 to October 2024, a total of 149 likely slicks were detected from the top likely polluting FxOs and fixed oil infrastructure, ten from each category; see Figure 8 and Table 2 for locations and data about likely slicks associated with Fixed oil infrastructure, see Figure 9 and Table 3 for locations and data about likely slicks associated with FxOs. 64 of these slicks were associated with FxOs and covered an area of 299 km^2 with a total volume estimate of 79,000 gallons (~1,881 bbl). The 164 slicks associated with Fixed oil infrastructure covered an area of 816 km^2 with a total volume estimate of 216,000 gallons (~5,143 bbl). Additional maps of the top 5 likely polluting FxOs and fixed oil infrastructure are available in Supplemental Tables 3 and 4, respectively.

For the top ten likely polluting sources, combined from both the FxO and fixed oil infrastructure locations, four of the top ten likely polluters are FxOs. See Figure 10 and Table 4 for locations and data about likely slicks associated with the top ten likely polluters. The top ten likely polluters had 149 associated slicks covering a total area of 819km^2 with a total volume estimate of 216,000 gallons (~5,143 bbl). While it is not possible to identify slicks on dates when no imagery was collected for all of the top polluting offshore oil facilities, as well as for both top likely polluting FxO and fixed oil infrastructure, we also extrapolate the number of slicks each location may have produced during the analysis period. These extrapolated slick counts are calculated by multiplying the duration of the analysis period (516 days) by the percentage of S1 Scenes with a slick observed during the period, rounded.



Rank	Structure ID	Owner	Slick count	Percent of S1 scenes with slicks	Cumulative slick volume (gallons)	Country (EEZ)
1	453607	PT Pertamina (Persero)	17	34.0%	15,280	Indonesia
2	322153	Chevron Petroleum Nigeria Ltd.	23	28.8%	44,240	Nigeria
3	200525	Addax Petroleum	15	19.5%	21,180	Cameroon
4	426464	Chevron Petroleum Nigeria Ltd.	15	18.8%	14,280	Nigeria
5	1053749	Abu Dhabi National Oil Company	19	16.5%	34,000	UAE
6	475522	Dubai Petroleum	18	15.5%	34,400	UAE
7	376771	CNR International	17	10.4%	21,710	United Kingdom
8	193470	Equinor Energy AS	15	9.1%	4,530	Norway
9	495356	Dubai Petroleum	10	8.6%	17,050	UAE
10	1052516	OKEA ASA	15	7.4%	9,020	Norway

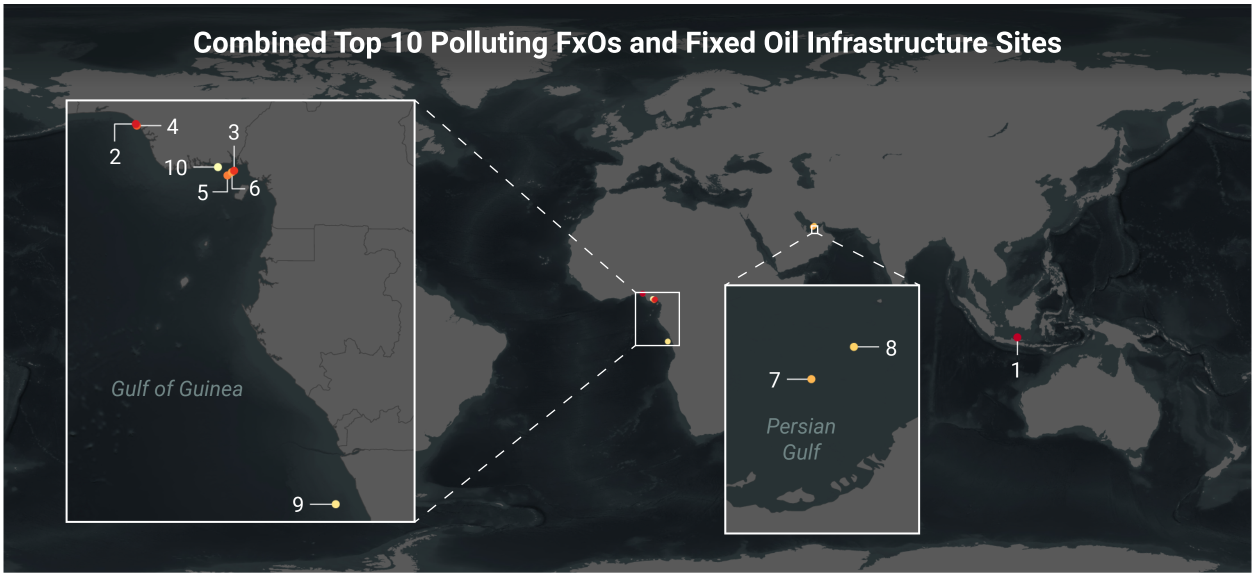
Figure 8: Top likely polluting fixed oil infrastructure sites, as ranked by the percentage of scenes with observed slicks from 2023/06/01 to 2024/10/09. Imagery of each of these is provided in Supplemental Figure 7. See Supplemental Table 1, as well as Supplemental Figures 3 and 4 for additional information.



Rank	MMSI	Owner	Slick count	Percent of S1 scenes with slicks	Cumulative slick volume (gallons)	Country (EEZ)
1	636014671 657246500*	Nigserv Energy Services Ltd. Koral Energy International*	14	18.4%	15,690	Nigeria
2	563030000	Adoon Pte. Ltd. Asharam Logistics Pte. Ltd.*	14	18.4%	3,990	Nigeria
3	310480000	Sonangol	5	13.2%	10,940	Angola
4	355338000 657270100*	Cenroc FPSO Solutions Ltd.	9	11.7%	22,420	Nigeria
5	356055000	Jubilee Ghana MV 21 Jubilee Ghana MV 21 BV*	2	5.0%	760	Ghana
6	311000563	Dana Petrolem/Neo Energy Zex Dana Petroleum Cosco HK Cieco*	12	4.9%	8,820	United Kingdom
7	311050200	OOG-TKP FPSO GmbH & Co KG OOG-TKP FPSO KG*	2	4.8%	950	Brazil
8	657126100	Shell Petroleum Nigeria	3	3.8%	1,010	Nigeria
9	603500186	Esso Exploration Angola	1	2.6%	11,640	Angola
10	657830000	Esso Exploration Nigeria	2	2.6%	2,810	Nigeria

* Multiple MMSI may be recorded for single vessels as a result of changes in ownership, flag state, or other factors. In these cases, we provide MMSI we found to be associated with the FxO. Similarly, multiple owners may be associated with a single source, either as a result of transfer or of joint ownership, we provide these lists as well.

Figure 9: Top likely polluting FxO operating locations, as ranked by the percentage of scenes with observed slicks from 2023/06/01 to 2024/10/09. See Supplemental Table 2, as well as Supplemental Figures 3 and 4, for additional information.



Rank	Type	MMSI or Structure ID	Owner	Slick count	Percent of S1 scenes with slicks	Cumulative slick volume (gallons)	Country (EEZ)
1	Infra	453607	PT Pertamina (Persero)	17	34.0%	15,280	Indonesia
2	Infra	322153	Chevron Petroleum Nigeria Ltd.	23	28.8%	44,240	Nigeria
3	Infra	200525	Addax Petroleum	15	19.5%	21,180	Cameroon
4	Infra	426464	Chevron Petroleum Nigeria Ltd.	15	18.8%	14,280	Nigeria
5	FxO	636014671 657246500*	Nigserv Energy Services Ltd. Koral Energy International*	14	18.4%	15,690	Nigeria
6	FxO	563030000	Adoon Pte. Ltd. Asharam Logistics Pte. Ltd.*	14	18.4%	3,990	Nigeria
7	Infra	1053749	Abu Dhabi National Oil Company	19	16.5%	34,000	UAE
8	Infra	475522	Dubai Petroleum	18	15.5%	34,400	UAE
9	FxO	310480000	Sonangol	5	13.2%	10,940	Angola
10	FxO	355338000 657270100*	Cenroc FPSO Solutions Ltd.	9	11.7%	22,420	Nigeria

* Multiple MMSI may be recorded for single vessels as a result of changes in ownership, flag state, or other factors. In these cases, we provide MMSI we found to be associated with the FxO. Similarly, multiple owners may be associated with a single source, either as a result of transfer or of joint ownership, we provide these lists as well.

Figure 10: Top 10 likely polluting FxO operating locations and fixed oil infrastructure sites, as ranked by the percentage of scenes with observed slicks from 2023/06/01 to 2024/10/09. See Supplemental Table 3 for additional information.

The FxO with the highest rank of likely slicks observed per scene collected is an FSO, the Virini Prem (IMO: 8613839 / MMSI: 636014671, 657246500) operating within Nigeria's Exclusive Economic Zone (EEZ) (longitude: 8.1745, latitude: 4.1025). A total of 14 slicks were observed between 2023/06/01 and 2024/10/09, found in nearly 1/5th (18.4%) of all the images collected during that time, and the estimated volume for these slicks is 15,694 gallons (~374 bbl), see Figure 11 below. Using the percentage of scenes where slicks were found, it is possible to extrapolate that the Virini Prem may have produced 95 slicks during the analysis period.

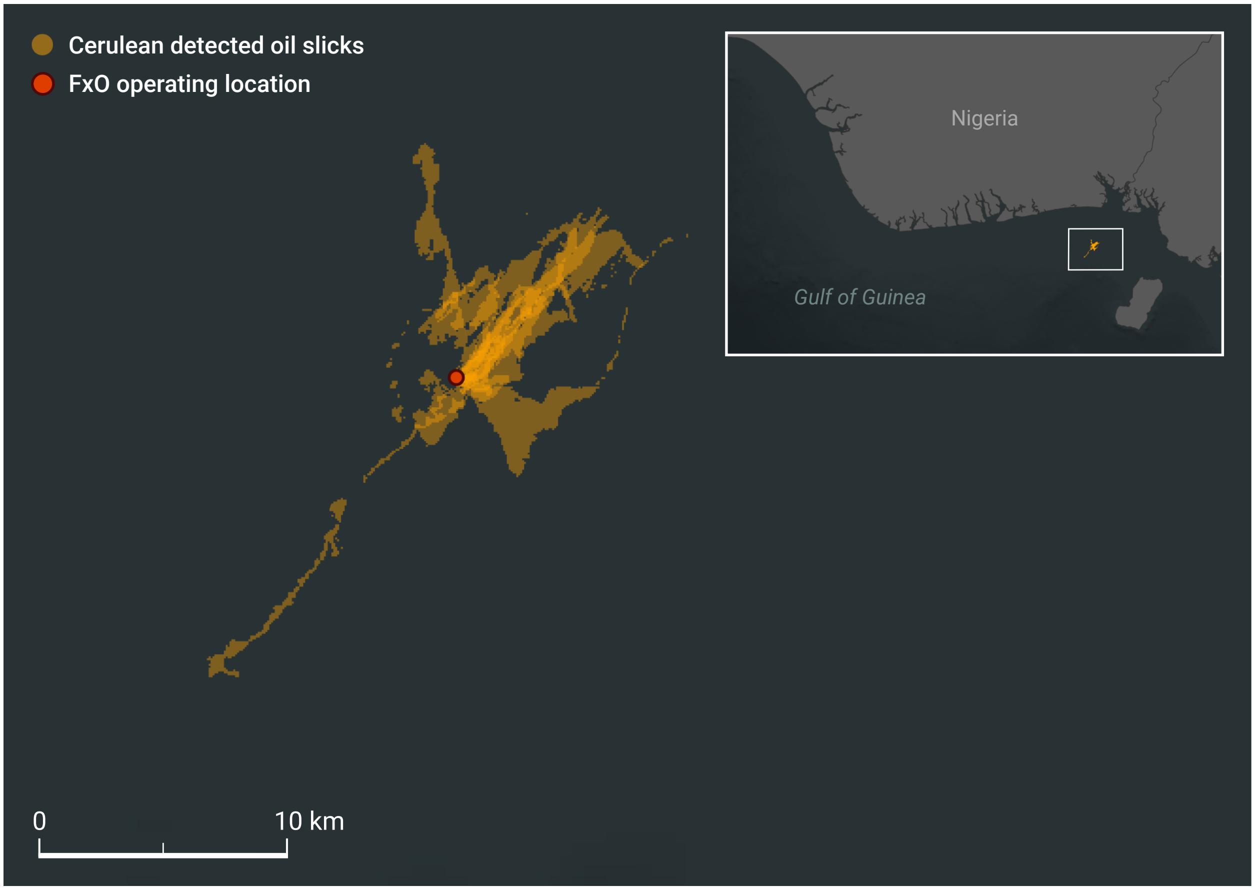


Figure 11: Cerulean detected slicks associated with Virini Prem (IMO: 8613839 / MMSI: 636014671, 657246500).

The FxO with the highest volume from likely slicks is an FPSO, the Princess Aweni (IMO: 7383401 / MMSI: 355338000, 657270100) operating within Nigeria's EEZ (longitude: 7.8292, latitude: 4.4048). A total of 9 slicks were observed between 2023/06/01 and 2024/10/09, visible in just over 11% of all the images collected during that time, and the estimated volume for these slicks is 22,420 gallons (~534 bbl), see Figure 12 below. Using the percentage of scenes where slicks were found, it is possible to extrapolate that the Princess Aweni may have produced 60 slicks during the analysis period.

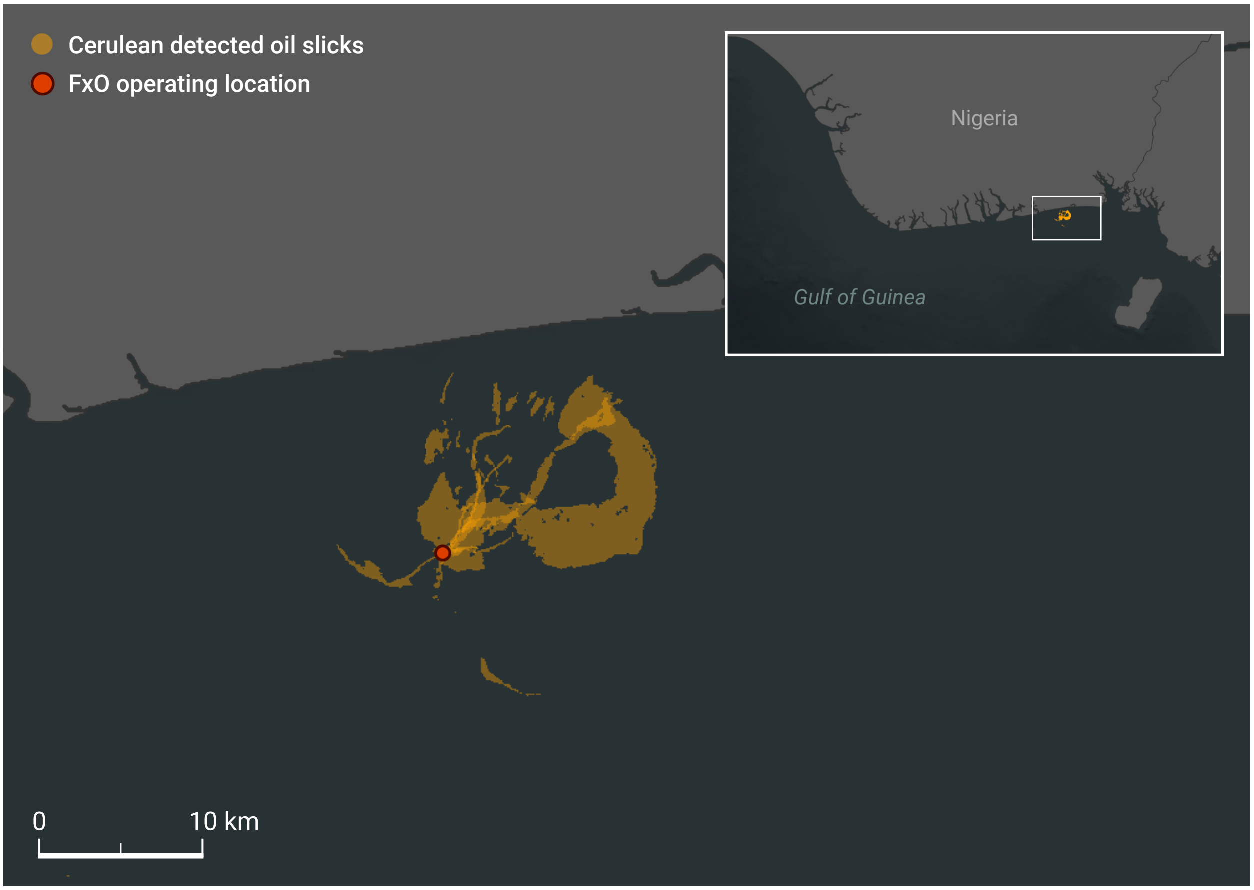


Figure 12: Cerulean detected slicks associated with Princess Aweni (IMO: 7383401 / MMSI: 355338000, 657270100).

Identifying information about the fixed oil infrastructure with the highest rank of likely slicks observed per scene collected was difficult to find; this platform is operating within Indonesia's EEZ (longitude: 112.9189, latitude: -6.6611). No name for the platform could be found via publicly available sites, but information about the owner links it to PT Pertamina (Persero), an Indonesian state-owned oil and gas company which owns the block where this platform is found [Ref]. A total of 17 slicks were observed between 2023/06/01 and 2024/10/09, found in over 1/3rd (34%) of all the images collected during that time, and the estimated volume for these slicks is 15,283 gallons (~364 bbl), see Figure 13 below. Using the percentage of scenes where slicks were found, it is possible to extrapolate that the platform may have produced up to 175 slicks during the analysis period.

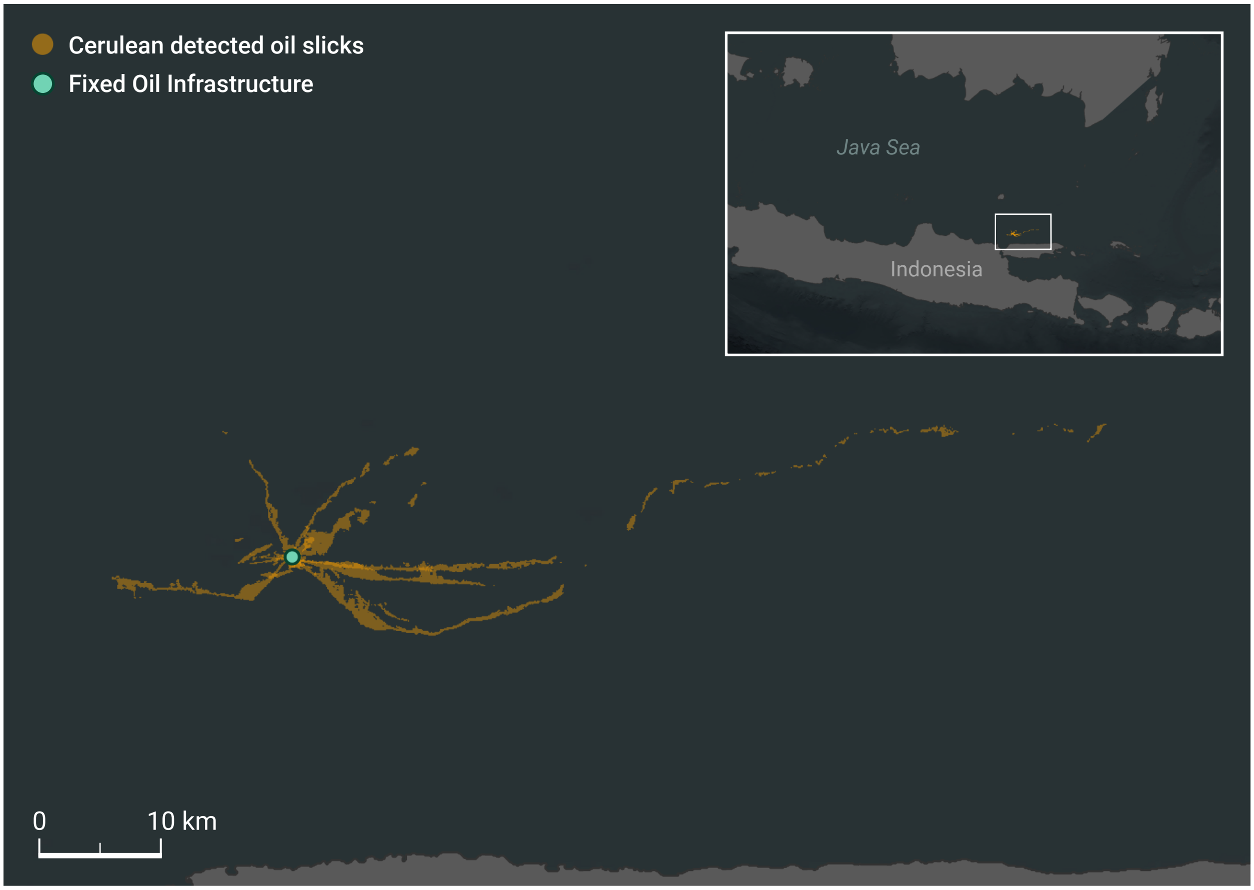


Figure 13: Cerulean detected slicks associated with PT Pertamina (Persero) owned platform.

Identifying information about the fixed oil infrastructure with the highest volume from likely slicks was also difficult to find, though information indicates the platform's name may be Isan West [Ref]; this platform is operating within Nigeria's EEZ (longitude: 4.8440, latitude: 5.9732). Information about the owner links it to Chevron Petroleum Nigeria Ltd [Ref]. A total of 23 slicks were observed between 2023/06/01 and 2024/10/09, found in nearly 1/3rd (28%) of all the images collected during that time, and the estimated volume for these slicks is 44,241 gallons (~1053 bbl), see Figure 14 below. Using the percentage of scenes where slicks were found, it is possible to extrapolate that the platform may have produced 148 slicks during the analysis period.

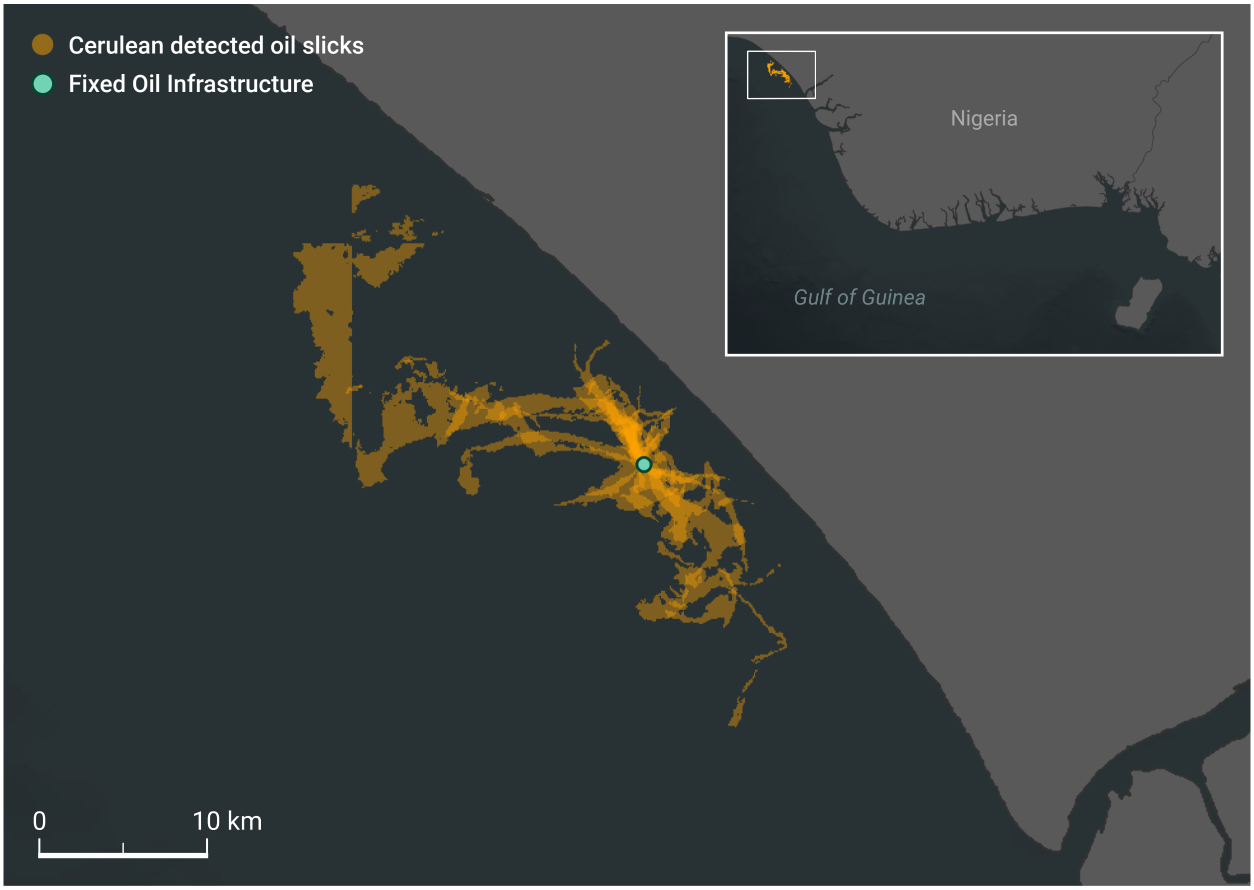


Figure 14: Cerulean detected slicks associated with Chevron Petroleum Nigeria Ltd owned platform. Of note, the western most slick [Ref] which displays with sharp vertical line is a valid slick detection, however an artifact in scene processing causes a portion of the slick to be missed by the detector.

Vessel Traffic and Emissions

AIS / Vessel Traffic

To determine which vessels visit offshore oil facilities, and what occurred during those voyages, we use GFW AIS data. Vessel interactions fall into the following categories: 1. Loitering near offshore oil facilities (vessel remained stationary within 500 m of an offshore oil facility for at least 1 hour), 2. Encounters with FxOs while not at an offshore oil facility (an FxO and another vessel loiter in one place that is not within 500 m of an FxO operating location or fixed oil infrastructure).

To determine when these vessels visited ports, a port visits table is obtained from GFW [Ref], which uses several public lists of ports as well as highly trafficked anchorages, which generally finds most ports, but does occasionally label offshore infrastructure as a port due to high traffic volumes. Hand labeling was done on some of the infrastructure that had abnormally high numbers of visiting vessels to determine if these were ports or infrastructure and tables were updated accordingly.

Voyages are then determined from the vessel interactions and port visits as the journey of that vessel from port to offshore oil facility to port. Often, multiple offshore oil facilities are visited during one voyage. The voyage table is built by first building a chronological list of port visits and offshore oil facility visits for each vessel that visits an offshore oil facility, and then retaining AIS location for each port to port voyage. Because of some of the uncertainties related to ports versus infrastructure, as well as because there are sometimes gaps in the AIS locations (intentional or unintentional), some voyages are calculated to be multiple years in duration. It is possible that some of these are real, and may signify behaviors of concern [Ref], however these are not examined further in this paper, and voyages exceeding 2 months are excluded.

Vessel GHG Data

The greenhouse gas emissions associated with FxO operation are calculated using data from the Environmental Markets Lab (emLab) at University of California, Santa Barbara. We use their engine power lookup tables in combination with their vessel size and power to emission lookup tables, assuming that oil FxOs have similar emissions to oil tankers and FLNGs have similar emissions to gas tankers when anchored. These are then used to calculate emissions of FxOs for each operating period. The estimated CO_2 emissions calculated for each will be significantly lower than the actual emissions for FPSOs, because our estimates do not capture emissions related to the production or flaring of gas.

In addition to the emissions by FxOs, emissions are calculated for vessels that interact with infrastructure, including tankers that transport oil and support vessels used to transport crew and materials to and from platforms. The voyage level emissions are calculated using a model that was co-developed between GFW and emLab [Ref, Ref](McDonald et al. 2024). Their methods closely follow the 2020 International Maritime Organization's (IMO) "Fourth Greenhouse Gas Study" [Ref] and the 2017 ICCT "Greenhouse Gas Emissions From Global Shipping" study [Ref], and is adapted to leverage GFW's AIS datasets [Ref]. Emissions associated with interacting vessels are likely larger than our estimates due to AIS limitations, including encounters with smaller vessels not required to maintain AIS equipment and some vessels purposefully shutting off AIS despite regulations. Supplemental Figures 5 and 6 show vessel tracks associated with top fixed oil infrastructure and FxOs, ranked by total emissions from visiting vessels.

GHG Emissions

In addition to carbon emissions directly associated with oil and gas production, the vessels that interact with infrastructure have an environmental impact. Reasons for vessel visits include platform maintenance, crew and supply transportation, and the transfer and transport of oil from FxOs and some fixed oil infrastructure. Additionally, crew and supplies must be transported to and from offshore facilities. These vessels also contribute to the carbon footprint of offshore oil. Increased vessel traffic is also disruptive to ecosystems [Ref, Ref]. The map below, Figure 15, displays the tracks associated with vessel voyages that stopped at offshore oil facilities in 2023.

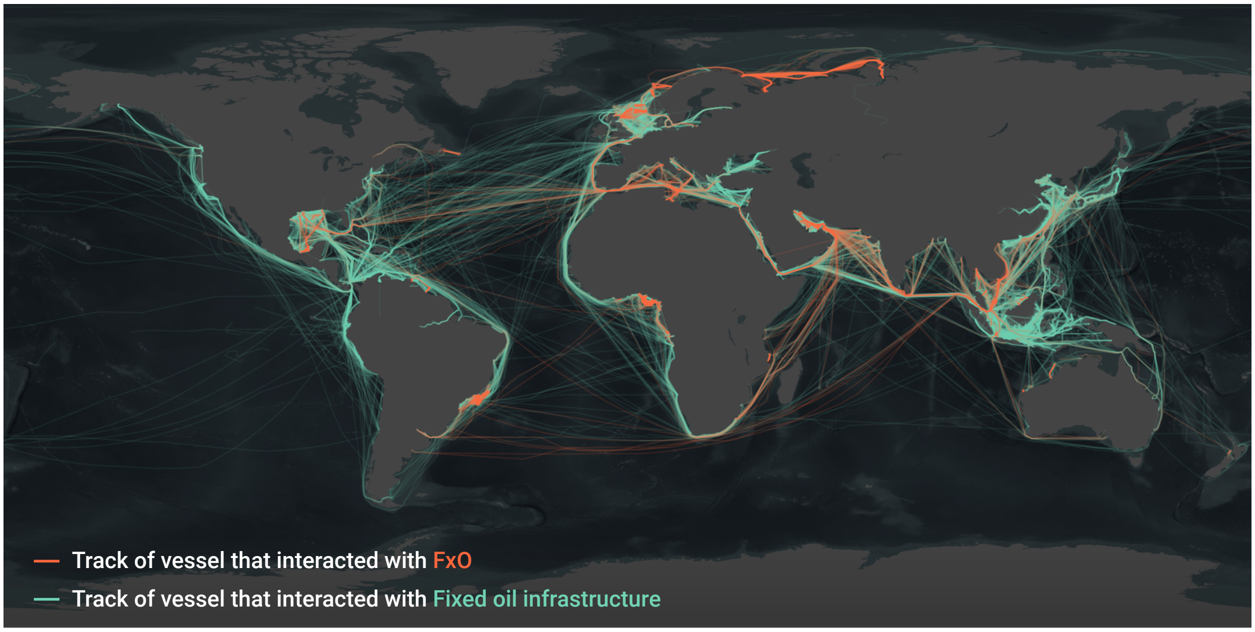


Figure 15: Vessel tracks of all vessels that visited offshore oil facilities in 2023.

Whereas most FxO operating locations are visited by tankers and support vessels each month, fixed oil infrastructure sites on average have far less traffic, with only 30-40% receiving any vessel visits over the course of a month, and 60-80% visited at least once in a calendar year (see Figure 16). The GFW oil infrastructure dataset includes a variety of structure types, and different infrastructure types may have different patterns of vessel interactions. The most commonly visited facilities are generally terminals.

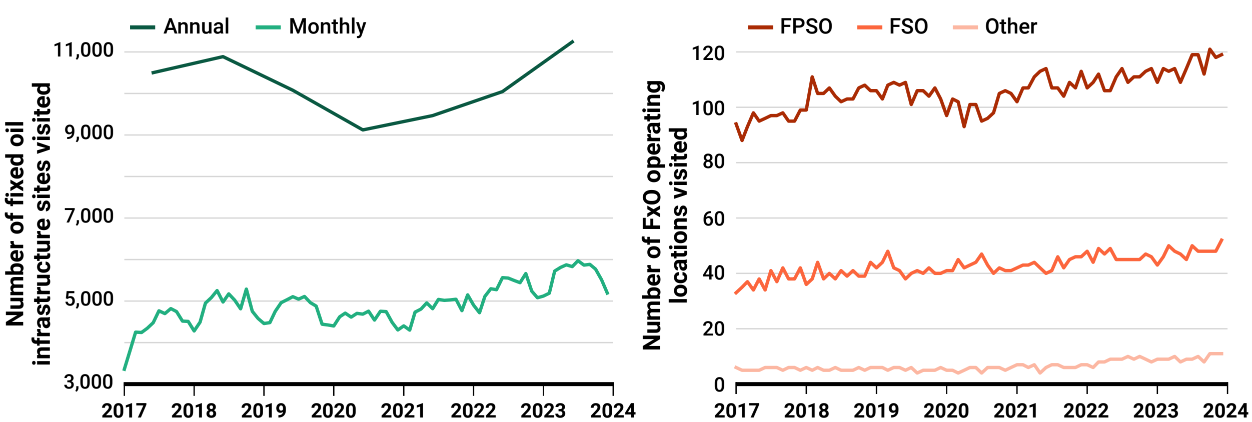


Figure 16: Number of fixed oil infrastructure sites (left) and FxO operating locations (right) that are known to have been visited by vessels during that month and year.

The monthly number of vessel interactions with infrastructure is shown below, see Figure 17. The apparently increasing trend in vessels visiting offshore oil facilities may at least partially be due to higher adoption rates of AIS. Larger vessels are required to maintain AIS, and therefore, tanker visit trends are likely closer to reality than the total vessel visit trends. Tanker visits to fixed oil infrastructure do appear to be increasing, despite the number of fixed oil infrastructure sites peaking in 2020. There is a pronounced seasonal cycle of vessels visiting infrastructure with around 20-30% more infrastructure visits in the summer months than in the winter. In 2023, there were at least 40,000 vessel visits to offshore oil facilities in the northern hemisphere summer months. One interesting trend is that known FxO encounters with vessels out at sea started increasing rapidly in late 2021, and the reason for this is unknown. This increase is noted in most parts of the world, but some of the most rapidly increasing encounters with FxOs outside of operating locations are in the Persian Gulf, Gulf of Thailand, and South China Sea.

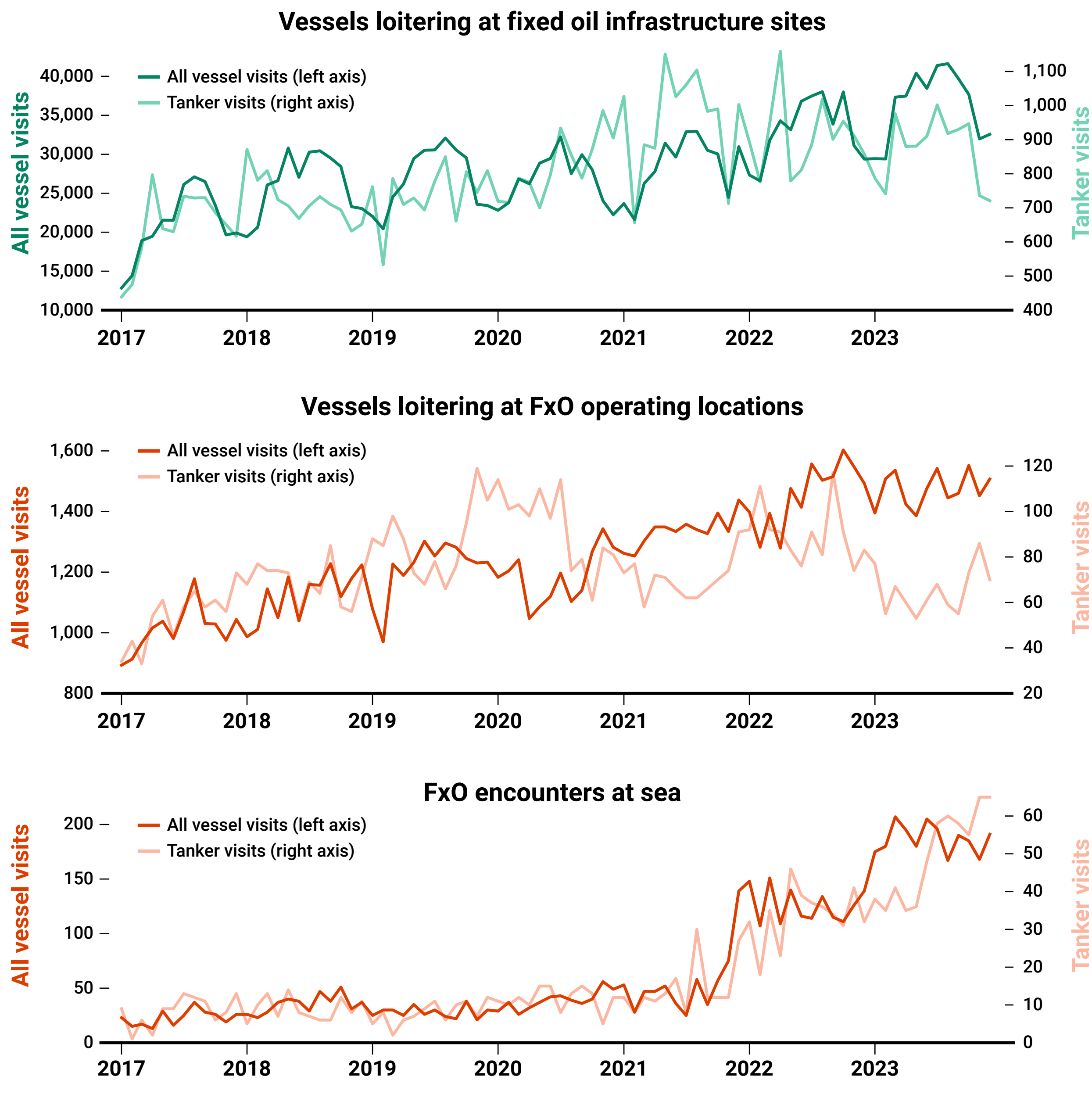


Figure 17: Number of vessel (and tanker specific) interactions with infrastructure in each month. FxO encounters at sea are events when FxOs had encounters with vessels not near their operating locations, i.e. any encounter at a location where the vessel did not linger for at least 60 days.

These vessels also have a carbon footprint, which has been steadily increasing due to increased vessel traffic and larger vessels being used to transport oil. In 2023, voyage-level emissions from vessels visiting offshore infrastructure are estimated to be around 9 million metric tons of CO_2, see Figure 18. This estimate is likely substantially lower than the actual emissions because these results are based on AIS, and not all vessels are publicly tracked [Ref].

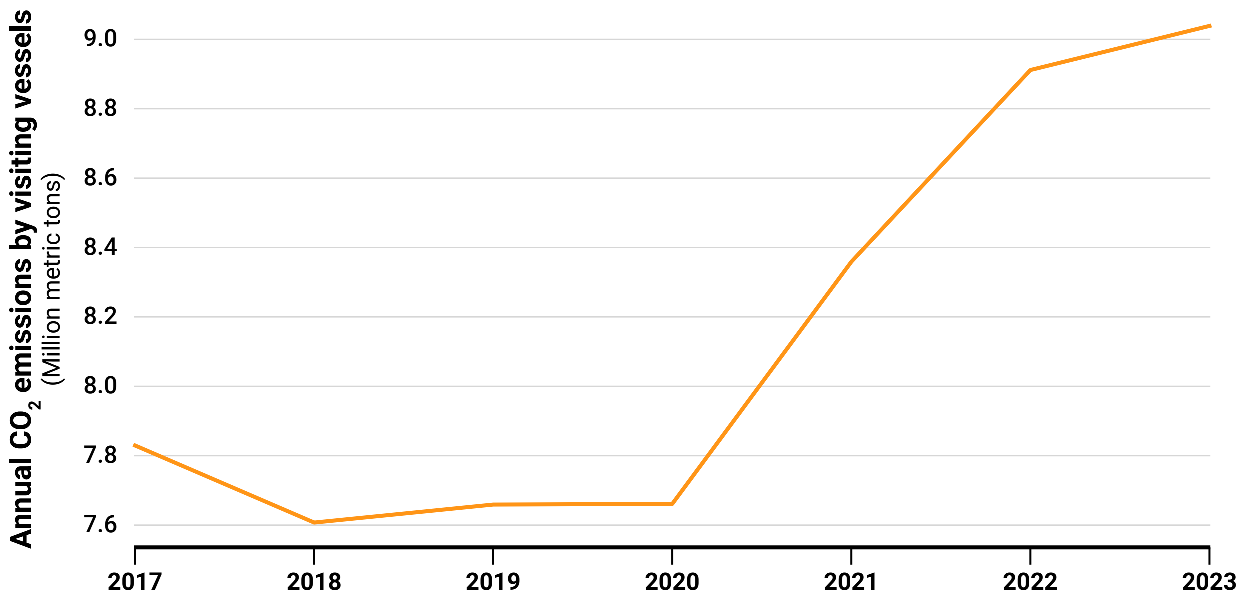


Figure 18: Annual CO_2 emissions by vessels that visited offshore oil facilities

Infrastructure sites with high visiting vessel emissions can be associated with a small number of very long voyages, many shorter voyages, or visits by large vessels. The fixed oil infrastructure and FxO operating locations with the highest visiting vessel emissions in 2023 are shown in the Supplemental Material.

The infrastructure location with the top visiting vessel emissions in 2023 was Richmond Long Wharf [Ref], an oil import terminal in California, which had 516 visiting vessel voyages that year. The second highest emitter from visiting vessels in 2023 was an LNG terminal in India associated with Petronet LNG Limited, which had just 8 voyages, however, each voyage crossed long distances, mostly from India to the US. Of the top 10 most visited fixed oil infrastructure sites, one is an oil offloading port (buoy connected to hoses to offload oil) and the other nine are terminals (of which, five are connected to shore directly and four are offshore). All of these locations are where oil and gas are loaded or offloaded for transport, and not the platforms that are producing oil.

FPSOs are involved in both the production and offloading of oil, so they tend to see more traffic than production platforms. Additionally, FPSOs have the potential to operate in deeper water, potentially leading to longer voyages. For these reasons, despite the fact that there is more than an order of magnitude more fixed oil infrastructure sites than FxO operating locations, 3 of the top 10 offshore oil facilities are FxO operating locations. The top emitting FxO operating location in 2023 was one about 20 km off the coast of Italy, whose vessel visits emitted an estimated 91,000 metric tons of CO_2. Though there were only 29 voyages to that FxO operating location, most of them crossed the Atlantic.

Flaring Activities

During the extraction process of oil, natural gas in the form of methane is also released. Methane can be handled by capturing it for sale, re-injecting it into wells, burning it to convert it to CO_2 (a practice known as flaring), or venting it directly into the atmosphere. There are significant initiatives aimed at limiting the practice of flaring [Ref]. Understanding the patterns of flaring activity associated with FxOs and fixed oil infrastructure is crucial for both the evaluation of climate initiatives focused on the reduction of GHG emissions and also for monitoring behaviors of concern.

We observe flaring events at both FxO operating locations and fixed oil infrastructure using data derived from a combination of the Visible Infrared Imaging Radiometer Suite (VIIRS), Landsat 8, Landsat 9, and Sentinel-2. Flaring events observed by VIIRS are provided to SkyTruth by Colorado School of Mines' Earth Observation Group's VIIRS Nightfire dataset [Ref], which provide nightly data detailing flaring events across the world. One limit to observing flaring with the Nightfire dataset is cloud cover; we augment the dataset with one of flaring events detected using thresholds in Shortwave Infrared (SWIR) bands for the Landsat and Sentinel-2 satellites, see Figure 19. This provides some additional information about dates when flaring occurs. These SWIR detected events are compared to the Nightfire data and used to create monthly summary data for each FxO and fixed infrastructure location, see Figure 20.

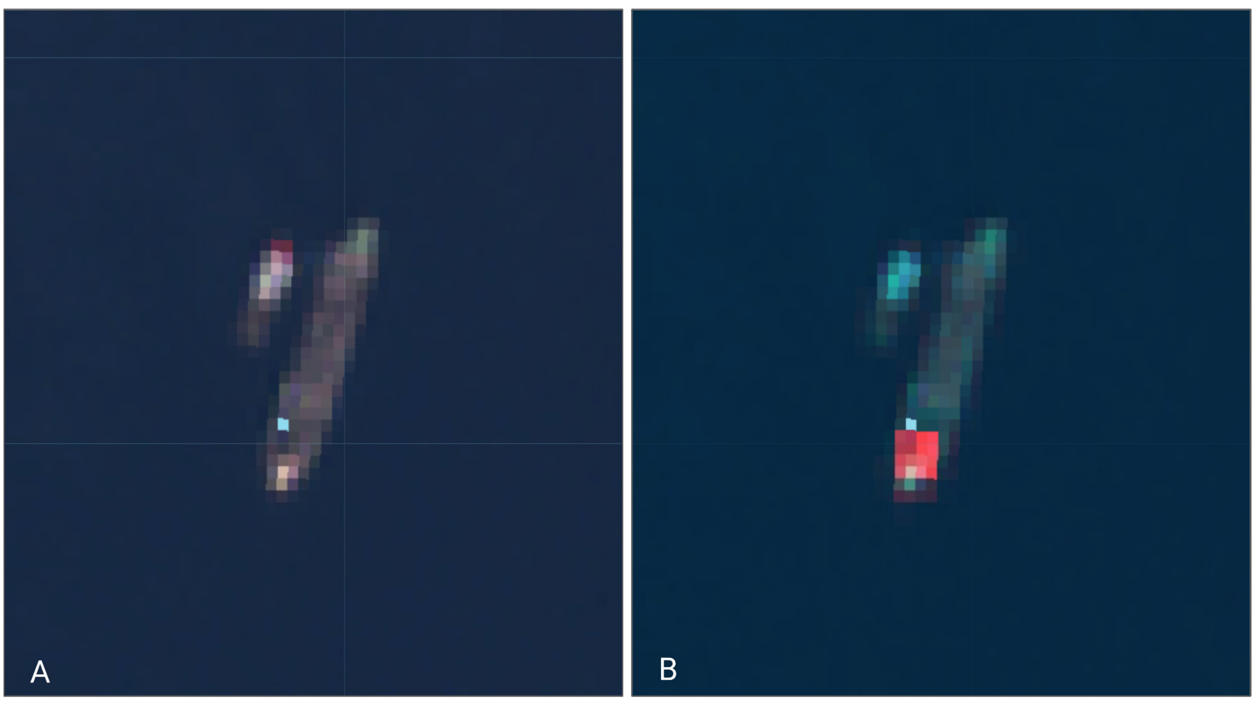


Figure 19: Flaring event observed by Sentinel-2 at an FPSO, the Bleo Holm (MMSI: 306239000), in the North Sea on 2023/06/16. (A) A true-color (R,G,B) image of the vessel, (B) the flare is seen when viewing the ship in a false-color image where Shortwave Infrared Band 2 is substituted for the red band (SWIR2, B, G).

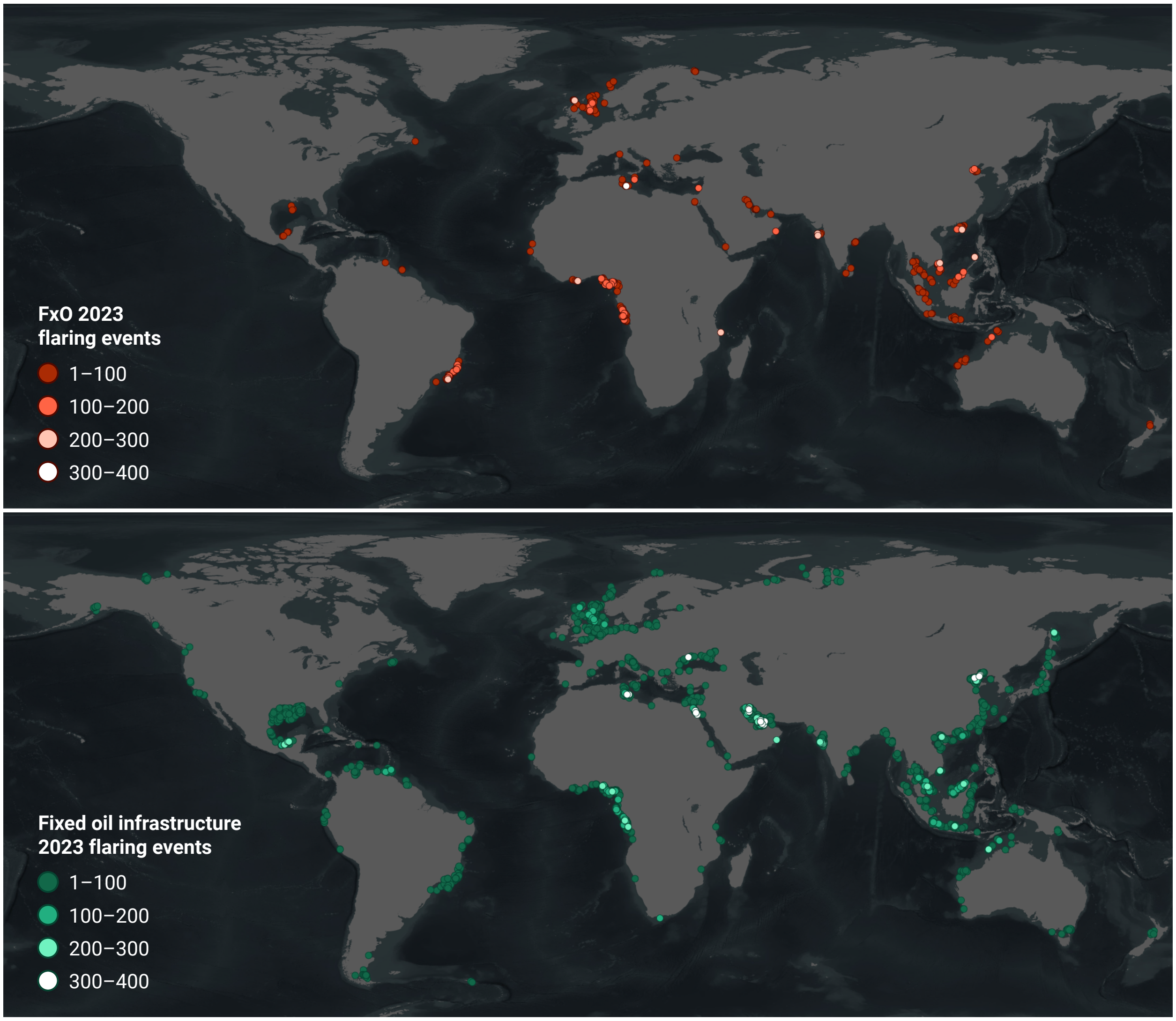


Figure 20: (Top) Observed flaring events in 2023 at 291 FxO operating locations: 240 locations had 1-100 observed flaring events, 41 had 100-200 events, 9 had 200-300 events, and 1 had 300-400 events in 2023. (Bottom) Observed flaring events in 2023 at 10,218 GFW fixed oil infrastructure locations: 9,925 locations had 1-100 observed flaring events, 199 had 100-200 events, 67 had 200-300 events, and 27 had 300-400 events in 2023.

Flare Volume Estimates were provided by EOG Nightfire data; the flare volume data is provided as an annual file for the years 2017 - 2023, these were downloaded and data points that did not intersect land were selected, see Figure 21. For each year the "flare upstream" data was used to determine the volume in billion cubic meters (BCM), then converted to million metric tons CO2 Equivalent (CO_2e) emissions [Ref]. The data also identifies the country's waters where flaring occurs, which is used to determine the volume by country. In 2023, the total flare volume estimate was 23.1 BCM, 58.8 million metric tons CO_2e; the countries with the highest CO_2e emissions were Iran - 7.9 million metric tons CO_2e (3.1 BCM), Nigeria - 6.4 million metric tons CO_2e (2.5 BCM), and Mexico - 5.0 million metric tons CO_2e (1.9 BCM), see Figure 22.

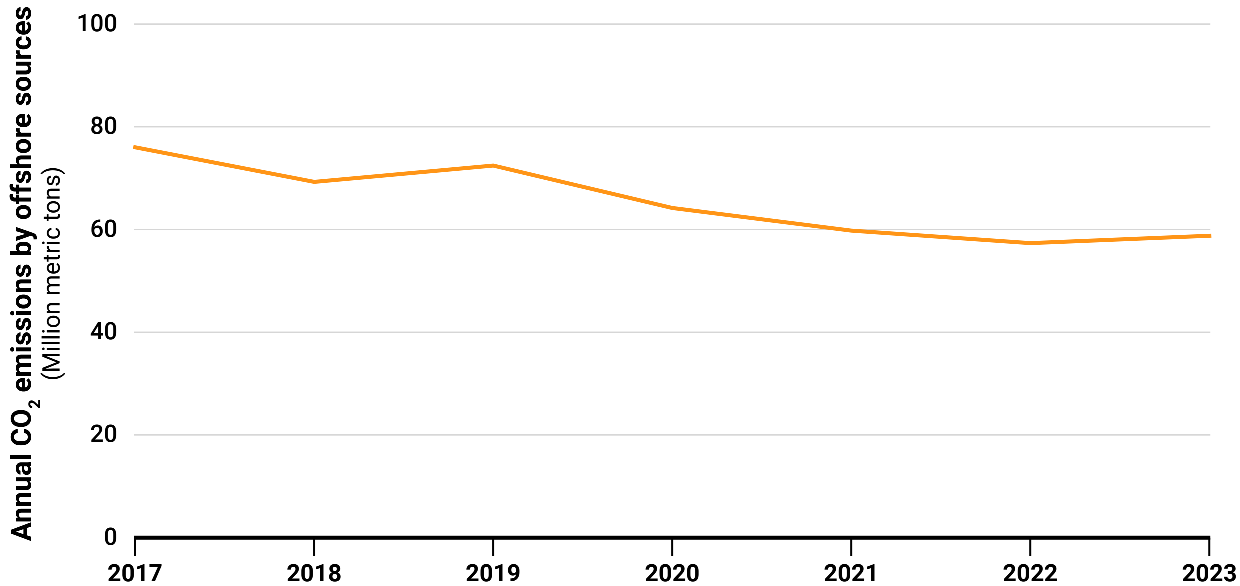
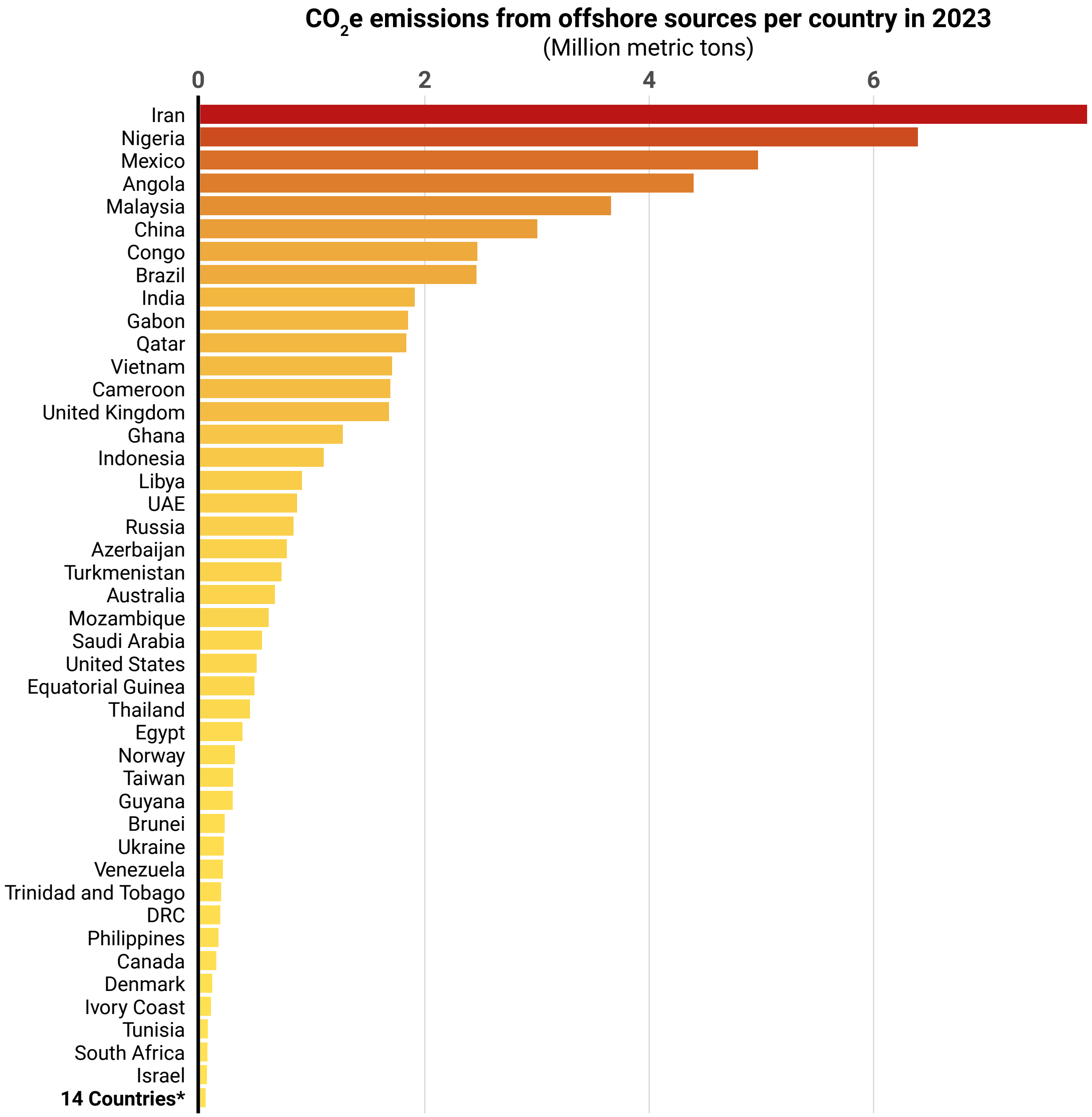


Figure 21: CO_2e Emissions (Million Metric Tons) from offshore sources, by year, 2017–2023.



* **14 Countries had less than 0.5 Million metric tons of CO2 emissions in 2023:** Oman, Timor-Leste, Argentina, Poland, Myanmar, Romania, Netherlands, Kazakhstan, Namibia, New Zealand, Turkey, Peru, Cyprus, South Korea.

Figure 22: CO_2e Emissions (Million Metric Tons) from offshore sources in 2023 by country.

Future Work

The data and analyses detailed in this paper constitute the initial but robust steps in understanding the full impacts of offshore oil production. As countries around the world commit to goals designed to mitigate the most severe impacts of climate change, there is a critical need for effective monitoring of the fossil fuel industry to ensure progress towards these goals is being made.

As this project continues, SkyTruth is committed to improving our existing datasets and expanding our analyses of the offshore industry's impacts. Plans for future work include expanding our analysis of GHG emissions to FxOs and platforms themselves. As a first step in this direction, CO_2 and CH_4 emissions associated with offshore oil facilities were obtained from Rocky Mountain Institute and the results aggregated by country are shown in the supplemental material [Ref]. Initial data provided by RMI indicates that the CO_2 and CH_4 emissions associated with the production and transmission of offshore oil and gas are experiencing an overall increase among the top 10 emitting countries; however the emissions trend for all other countries is experiencing a slight decrease,see Supplemental Figure 1 and 2. We also plan to conduct analyses that will examine flaring frequency in greater detail to flag atypical events that may require closer monitoring or intervention. Other behavioral analyses of FxOs and platforms will also be conducted, to investigate potential relationships between operational activities and vessel encounters with observed behaviors such as flaring or slick occurrences. Improvements being made to our Cerulean model will allow us to more effectively identify slicks associated with stationary sources, and continued processing of the Sentinel-1 image archive will facilitate more comprehensive analyses of top likely polluting sources and will support better management and regulation of the offshore industry.

One key area of analysis which we do not address in this paper is related to the detection and monitoring of fugitive methane emissions. New data from satellites such as MethaneSat and Carbon Mapper will be instrumental in future work to detect leaks from offshore oil facilities and measuring their impacts on the climate. We also anticipate that improvements to the fixed oil infrastructure dataset will allow for analysis of infrastructure that is located within 1km of shore, which are not currently captured by GFW's dataset. SkyTruth plans to assist with improvements to the fixed oil infrastructure dataset by working to identify sub-types of fixed oil infrastructure, to include categories like active or abandoned platforms, mooring buoys, and offshore terminals.

Our findings imply a need for increased scrutiny of the site-specific pollution burden imposed by offshore fossil fuel development and transport. Across the world, FxOs and poorly maintained infrastructure are causing significant local pollution with likely detrimental impacts on sectors including food systems, public health, and tourism. Given that the number of FxOs in particular is increasing, it should not be assumed that this problem implicates only older, operating infrastructure. These findings should inform policy considerations about proposed expansions to offshore extraction around the world. Amidst the weighing of an extractive project's GHG emissions against purported economic benefits, policymakers and engaged citizens should consider chronic oil slicks, increased vessel traffic, and methane flaring as some of the potential impacts. As this research continues, it will help communities gain insight into the true costs of offshore oil and gas extraction.