Charting the Uncharted: Oil Sanctions and Dark Shipping

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Background

- Western authorities have imposed numerous oil-related sanctions on Iran, Syria, Venezuela, and Russia, aiming to curb their oil revenues (and, thus, their economic and geopolitical power).
- These sanctions have reduced the recorded oil supply but also fueled the increase of covert maritime operations.
- Dark shipping: vessels evade detection and bypass sanctions by turning off their AIS (Automatic Identification System) transceivers and using other deceptive practices.

Automatic Identification System (AIS)

Figure 1: AIS transceiver

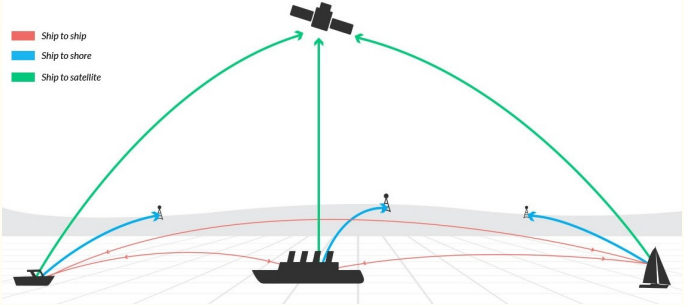

Figure 2: How AIS works

AIS gaps

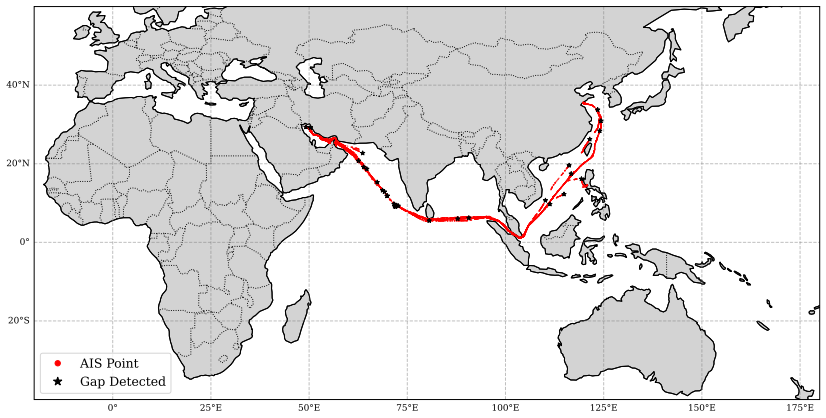

Figure 3: Illustrative example of AIS transmission gaps: *Roma* (IMO: 9182291)

Notes. AIS observations (red points) for *Roma* recorded in 2023, along with the first observations following each 10-hour AIS data gap during which *Roma* disabled its AIS transceiver (asterisks).

Contributions

1. We develop a novel machine learning-based, multi-attribute ship clustering model to identify dark ships and their suspicious trips.

2. We quantify the scale and geographical distribution of global dark-shipped oil trade by measuring real-time exports and imports transported by dark ships.

3. We examine, using both LPs and a simulated model, the propagation of sanctions through global oil markets while accounting for the endogenous response of dark shipping.

4. We assess, using LPs and SVARs, the dynamic causal effects of oil sanctions to both sanctioning (the U.S. and EU) and non-sanctioning (China) entities.

5. We analyze the transmission mechanisms, focusing on the global supply chains.

Three challenges in quantifying dark-shipped oil

1. No aggregate data available:
    - Lack of reliable oil export data from sanctioned nations.
    - Importing countries often withhold accurate data due to the covert nature of transactions.
2. Dark ships conceal their identities:
    - Frequently disable or manipulate AIS transceivers, hiding location, heading, and speed.
3. High cost of alternative data sources:
    - Satellite imagery: \$10-\$25 per square kilometer, or equivalently, more than \$3,000 per trip.
    - Ownership and insurance data: accessible only through expensive proprietary databases (e.g., S&P Global).
    - Allows identification of only individual vessels or small groups engaged in dark shipping.

AIS data

- We use AIS data of crude oil tankers:
  - Covers over 2,150 tankers, nearly the entire global crude oil tanker fleet.
  - Spans January 2017 to December 2023, updated as frequently as every two seconds.
  - Contains $\approx$ 330 million observations, including IMO number, timestamp, speed, heading, and coordinates.
- We also use metadata on the ships (e.g., vessel age, flag, idle trip ratio, etc.).
- The vast volume of records naturally lends itself to machine learning for automatic classification.

Factors to consider for the ML model

The identification of dark ships is a labeling problem, but ...

- No training set available.

  $\Longrightarrow$ Unsupervised learning.

- Captures similar deceptive practices outlined by the U.S. Department of State in May 2020:
  - Disabled AIS transceivers or "AIS spoofing."
  - Ship-to-ship transfers in high-risk areas associated with sanction violations or unauthorized activities.
  - Kinetic anomalies.
- Focus on the entire dark tanker fleet.
- Analyze trips to quantify dark-shipped oil exports and imports.

  $\Longrightarrow$ Centroid-based K-means clustering.

A multi-attribute ship clustering model

1. Data preprocessing and trip construction:
   - Noise elimination.
   - Frequency reduction.
2. Feature extraction and trip classification:
   - Three-level trip classification process.
3. Dark ship identification.

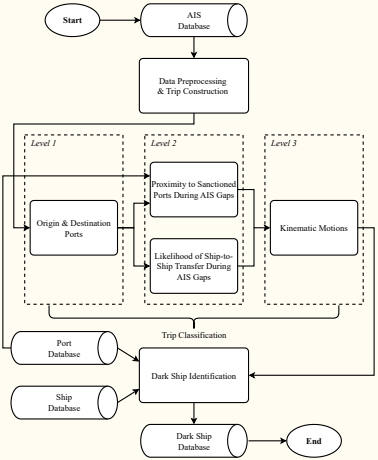

Figure 4: Model flowchart

Direct visit to a suspicious port during AIS gaps

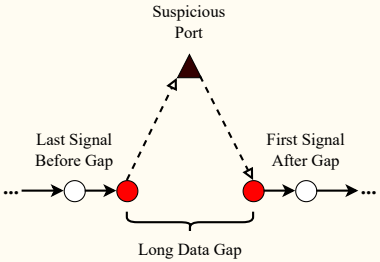

Figure 5: Mechanism

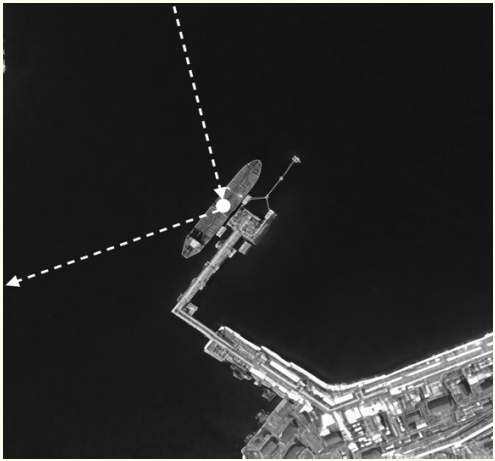

Figure 6: *Roma* (IMO: 9182291), Kharg Island (Iran), Aug 20, 2022

Ship-to-ship transfer during AIS gaps

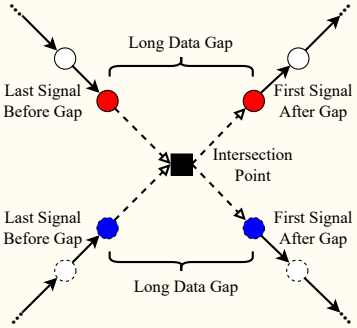

Figure 7: Mechanism

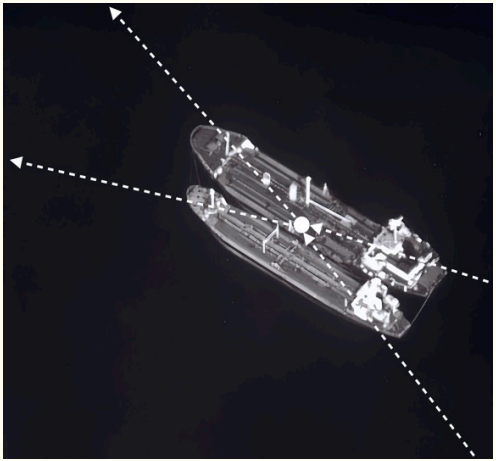

Figure 8: *Abyss* (IMO: 9157765) & *Shanaye Queen* (IMO: 9242118), Persian Gulf, Jan 28, 2022

Navigational anomalies

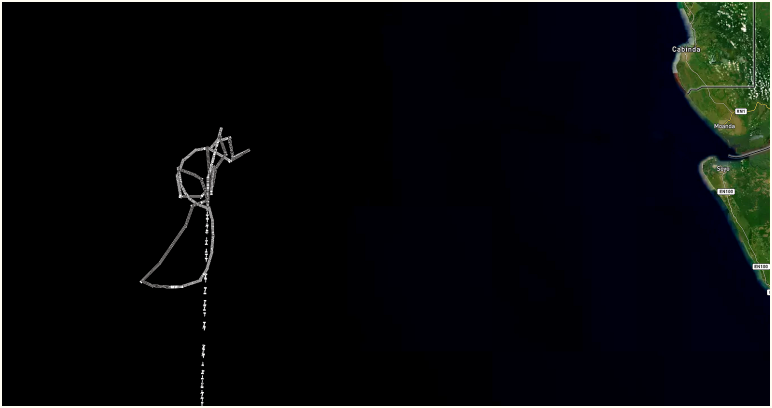

Figure 9: AIS spoofing by *Blazers* (IMO: 9307645)

Notes. Trajectory of *Blazers*, flagged as a dark ship by our algorithm. In early September 2023, the vessel spent an extended period drifting in ballast in international waters off the coast of Angola, indicating a high likelihood of AIS spoofing.

Charting the uncharted

Figure 10: *C.Galaxy* (IMO: 9404924), Kharg Island (Iran), Nov 18, 2020

Figure 11: *Azuron* (IMO: 9589750), Kozmino (Russia), Dec 7, 2023

Figure 12: *Panda* (IMO: 9284582) & *Elka Parana* (IMO: 9625724), Gibraltar, Mar 15, 2023

IMO	Source	Suspicion Years	Model Predictions	
			Full Model	Vessel Features Only
9182291	Lloyd's List Intelligence (2023)	2022, 2023	2022, 2023	2022, 2023
9224271	Lloyd's List Intelligence (2023)	2022, 2023	2022, 2023	N/A
9176993	Lloyd's List Intelligence (2023)	2021, 2022, 2023	2021	2021
9131357	Lloyd's List Intelligence (2023)	2022, 2023	2022, 2023	2022, 2023
9183295	Lloyd's List Intelligence (2023)	2021, 2022, 2023	2021, 2022, 2023	2021, 2022, 2023
9258521	Lloyd's List Intelligence (2023)	2022, 2023	2022, 2023	2022, 2023
9230969	Lloyd's List Intelligence (2023)	2022, 2023	2022, 2023	N/A
9307645	Lloyd's List Intelligence (2024a)	2023	2023	2023
9242118	Lloyd's List Intelligence (2024b)	2021, 2023	2021, 2023	N/A
9251274	S&P Global Market Intelligence (2023)	2022, 2023	2022, 2023	2022, 2023
9310147	S&P Global Market Intelligence (2023)	2022, 2023	2022, 2023	2022, 2023
9410870	S&P Global Market Intelligence (2023)	2022, 2023	N/A	N/A
9322827	S&P Global Market Intelligence (2023)	2021, 2022, 2023	2022	N/A
9235892	Triebert et al. (2023)	2023	2023	N/A
9249324	Triebert et al. (2023)	2023	2023	N/A
9259745	Triebert et al. (2023)	2023	2023	2023
9259733	Triebert et al. (2023)	2023	2023	2023
9157765	Meade (2023)	2021, 2022, 2023	2021, 2022, 2023	2021, 2022, 2023
9194127	Wijaya (2022)	2022	N/A	N/A
9304667	Wijaya (2022)	2022	2022	2022
9179701	Wijaya (2022)	2022	2022	2022
9255880	Wijaya (2022)	2022	2022	2022
9236353	Wijaya (2022)	2022	2022	N/A
9231767	Wijaya (2022)	2022	2022	N/A
9233208	Wijaya (2022)	2022	2022	N/A
		Total (Ship, Year)	42	42
		Identified (Ship, Year)	35 (83.3%)	23 (54.8%)
		Unidentified (Ship Year)	7 (16.7%)	19 (45.2%)

Dark fleet characteristics

- Dark ships tend to be older, operated by smaller commercial entities, flagged by higher-risk jurisdictions, and exhibit higher trip suspicion scores and idle trip ratios than white ships.

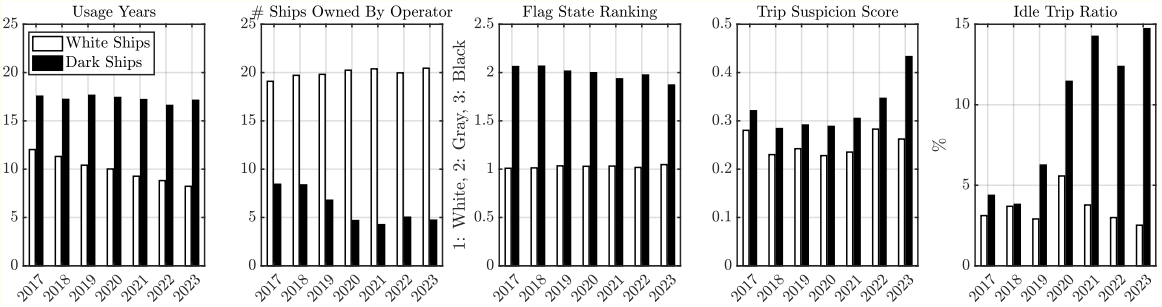

Figure 13: White vs. dark ships (centroid features)

Evolution of dark shipping

- On average, 555 dark oil tankers operated annually (2017-2023), representing one-fourth of the global crude oil tanker fleet.
- Fleet size fluctuated in response to geopolitical and economic developments.
- Despite fluctuations, the share of dark ships in the global fleet steadily declined.

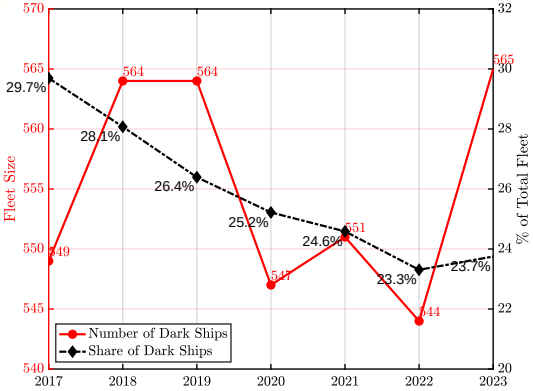

Figure 14: Scale and temporal dynamics of the dark fleet

Fleet composition

- 65.7% of tankers were never classified as dark ships during their operational years.
- 13.7% were classified as dark ships for some, but not all, years with available data.
- 20.6% were consistently classified as dark ships across all available years.

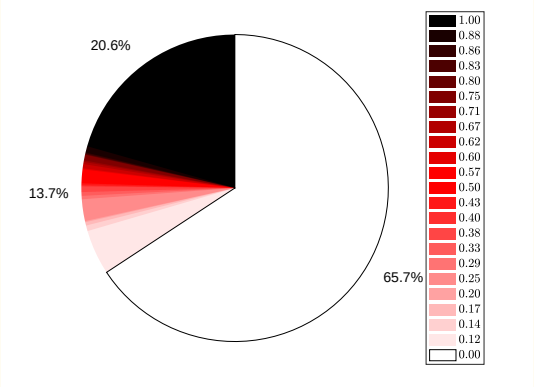

Figure 15: Composition of the dark fleet

2019 sanctions on PDVSA

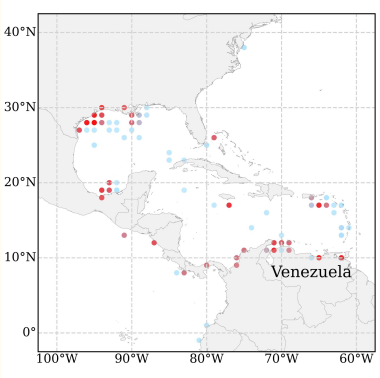

Figure 16: 2017

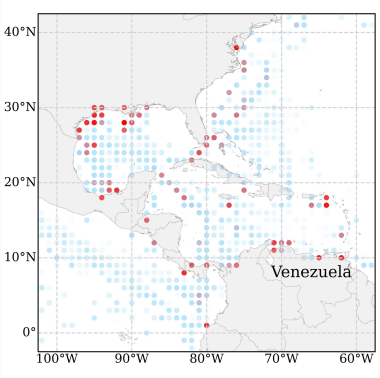

Figure 17: 2018

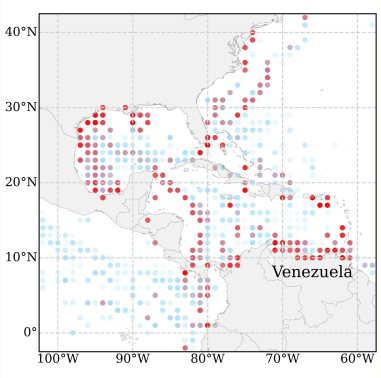

Figure 18: 2019

Notes. Each colored point represents a 1-degree geographical square containing at least one last AIS data point before a vessel disables its transceiver. The intensity of each point reflects the sum of port-based trip suspicion scores, which estimate the likelihood of a ship visiting a nearby sanctioned port during its AIS gap.

2022 oil embargo and price cap on Russian oil

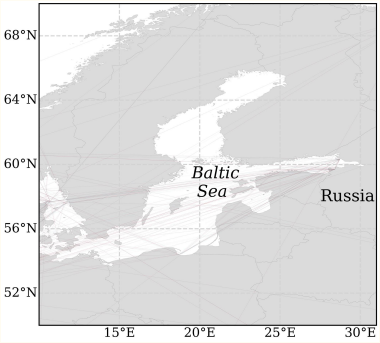

Figure 19: 2021

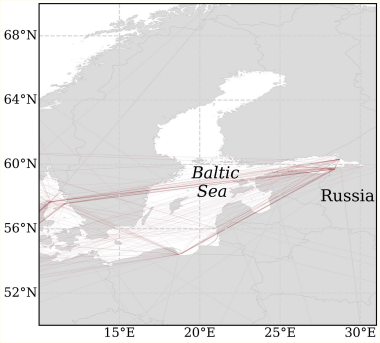

Figure 20: 2022

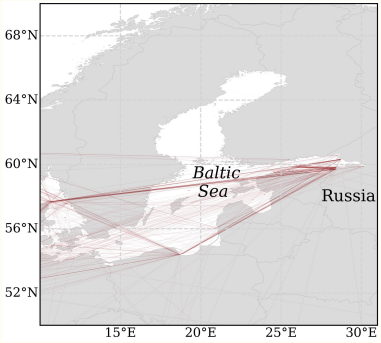

Figure 21: 2023

Notes. Each line connects two data points recorded before and after an AIS gap during an oil tanker trip, with its intensity representing the trip's port-based suspicion score. The AIS gap lengths for these trips exceed 120 hours.

Iran's "ghost fleet" switches into Russian oil since 2022

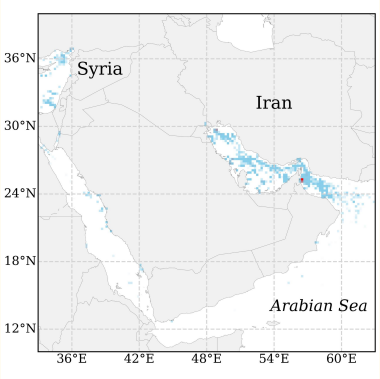

Figure 22: 2021

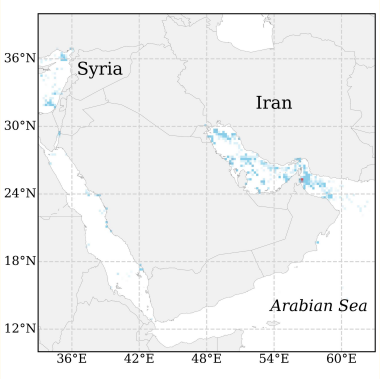

Figure 23: 2022

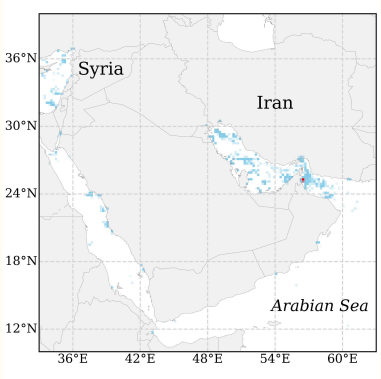

Figure 24: 2023

Notes. Each colored point represents a 0.2-degree geographical square containing at least one last AIS data point before a vessel disables its transceiver. The chromatic intensity of each point reflects the sum of port-based trip suspicion scores for the last data points within the square.

Overview of sanctions

Table 1: Overview of oil export/import sanctions on key countries.

Country	Sanctioning Parties	Timing	Details
Iran	U.S., European Union, Canada, etc.	Since 1995, intensified in 2012 and 2018	Sanctions targeting oil exports due to nuclear program
Syria	U.S., European Union, Canada, etc.	Since 2011	Prohibition on oil exports due to the Syrian civil war
North Korea	U.N. Security Council, U.S., European Union, etc.	Since 2017	Caps on oil and petroleum product imports due to nuclear program
Venezuela	U.S., European Union, Canada, etc.	Since 2019, intensified in 2020	Sanctions targeting PDVSA and oil embargo to pressure the government
Russia	U.S., European Union, U.K., Canada, etc.	Since 2022	Restrictions on oil exports due to the invasion of Ukraine

Notes. We exclude pre-2022 sanctions on Russia, as they mainly restricted access to Western technology, financing, and investment, whereas post-2022 sanctions directly targeted oil exports via import bans and price caps to curb revenue.

Dark shipping offsets sanction-driven supply cuts

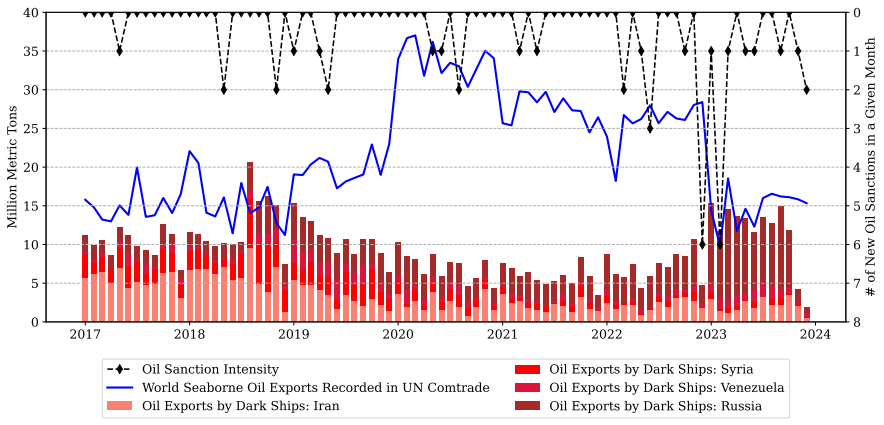

Figure 25: Dark-shipped oil exports, global seaborne oil exports, and sanction intensity.

Notes. Data on global seaborne crude oil exports from the UN Comtrade database, identified using HS code 2709 for petroleum oils and oils from bituminous minerals, crude.

A gravity model

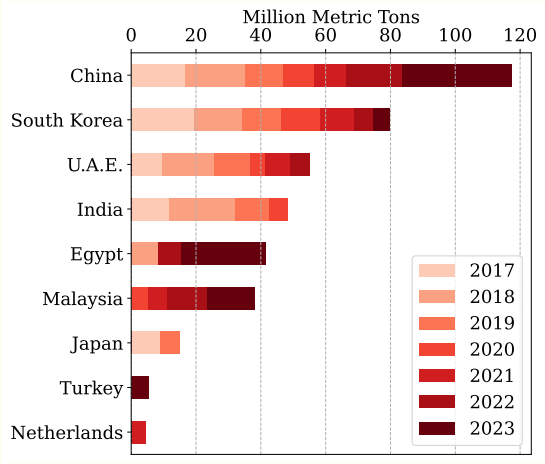

Figure 26: Major importers

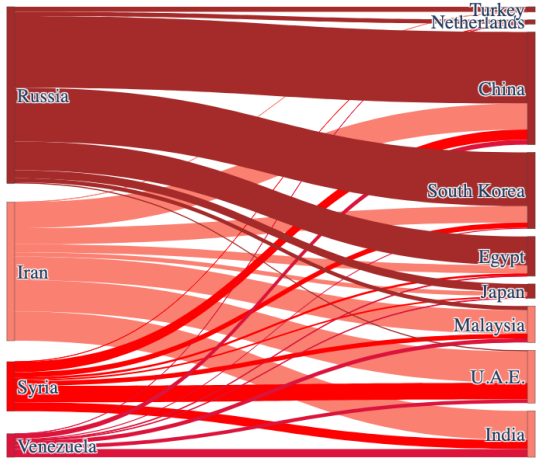

Figure 27: Dark-shipped oil flows

A dynamic causality analysis using LPs

- We assess the impact of an unexpected oil sanction intensity shock on global oil exports and prices using LPs (Jordà, 2005; Barnichon and Brownlees, 2019):

$$y_{i,t+k} = \beta_{i,k,0} \cdot SANCTION_t + \sum_{l=1}^{L} \boldsymbol{\beta}'_{i,k,l} \boldsymbol{y}_{t-l} + \alpha_k + u_{i,k,t}, \; 1 \leq i \leq n, \; 0 \leq k \leq K$$

- Four endogenous variables ($\boldsymbol{y}_t$):
  1. Oil sanction intensity index.
  2. Recorded world seaborne crude oil exports (UN Comtrade).
  3. Dark-shipped oil exports (Iran, Syria, Venezuela, Russia).
  4. Brent spot price.
- All series, except the sanction intensity index, are seasonally adjusted.

Recursive identification

- We identify an unexpected oil sanction intensity shock by:
  - Controlling only for lagged endogenous variables $\boldsymbol{y}_{t-l}$ (no contemporaneous controls).
  - Estimating the LP model starting from horizon $k = 0$.
- This is equivalent to placing the sanction intensity index first in a recursive ordering, allowing all other variables to respond contemporaneously to the shock.
- We include three lags of the endogenous variables in the LP model (i.e., $L = 3$) based on the HQIC criterion, and our results remain robust when considering longer lags.

Impact of oil sanctions on global oil exports and prices

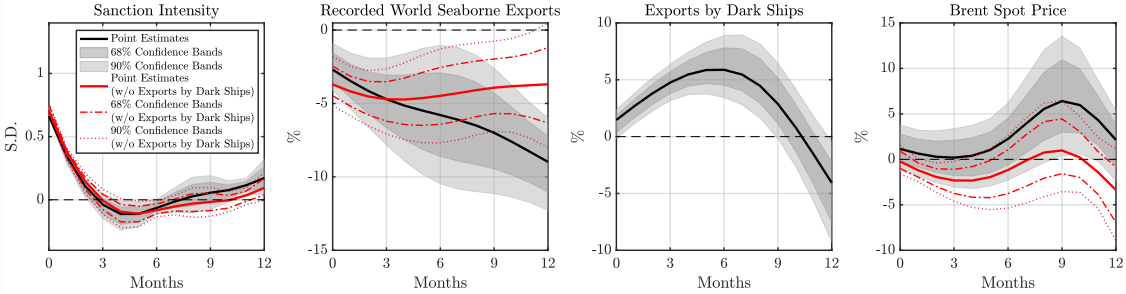

Figure 28: IRFs to a one-s.d. oil sanction intensity shock on global oil exports and prices: Empirical evidence

From oil market to macroeconomic impacts

- The LP model shows that dark shipping curbs global oil price increases by reallocating oil across markets.
- What are the broader macroeconomic effects of oil sanctions and dark shipping?
- Specifically, how do they affect inflation and output growth in both sanctioning (U.S. and EU) and non-sanctioning (China) economies?
- We build LP models for the U.S. and the EU by adding macroeconomic aggregates, oil sanction intensity index, recorded world seaborne crude oil exports (UN Comtrade), dark-shipped oil exports (Iran, Syria, Venezuela, Russia), WTI spot price.

Supply-driven growth for the U.S.

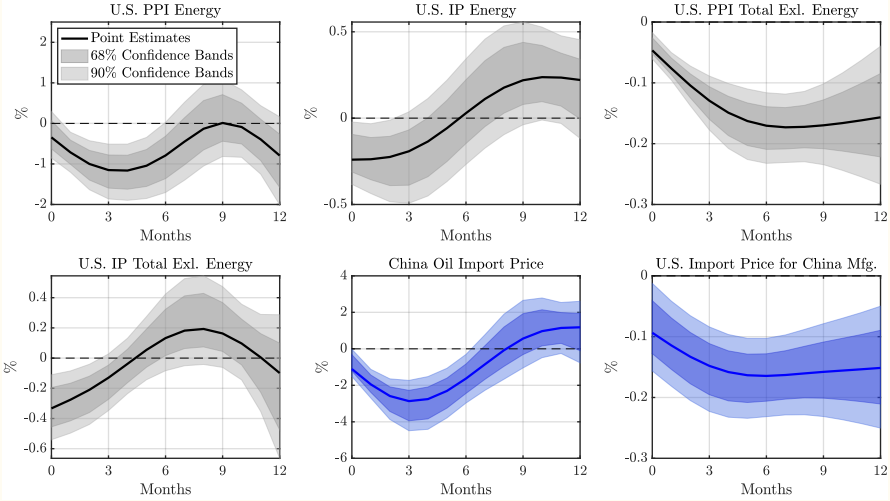

Figure 29: IRFs to a one-s.d. oil sanction intensity shock on the U.S. economy: Propagation channels

Trump says China can buy Iranian oil, but urges it to purchase US crude

By **Timothy Gardner**

June 25, 2025 3:41 AM EDT · Updated June 25, 2025

Supply- and demand-driven growth for the EU

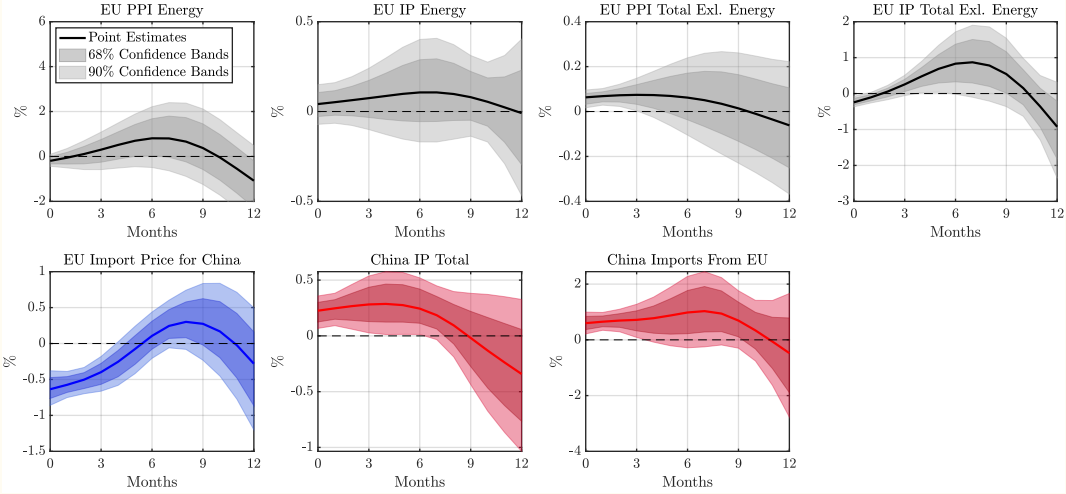

Figure 30: IRFs to a one-s.d. oil sanction intensity shock on the EU economy: Propagation channels

Conclusion

- Our approach combines a novel ship clustering model, new statistics, and advanced time series methods to assess causality.
- Dark shipping:
  - Stabilizes global oil prices by reallocating supply across segmented markets.
  - Unexpectedly boosts output in the U.S., EU, and China through global supply chains.
- These results:
  - Echo the classical idea that trade in goods can bypass factor trade barriers.
  - Emphasize sanction impacts through oil markets and supply chains, beyond just Russia vs. the EU.
  - May help explain weak enforcement and tolerance of dark fleets by sanctioning nations.