Targeting the Global Methane Pledge through Key Pathways in Inter-country Production and Consumption Networks with Feasible Technologies and Minimum Cost

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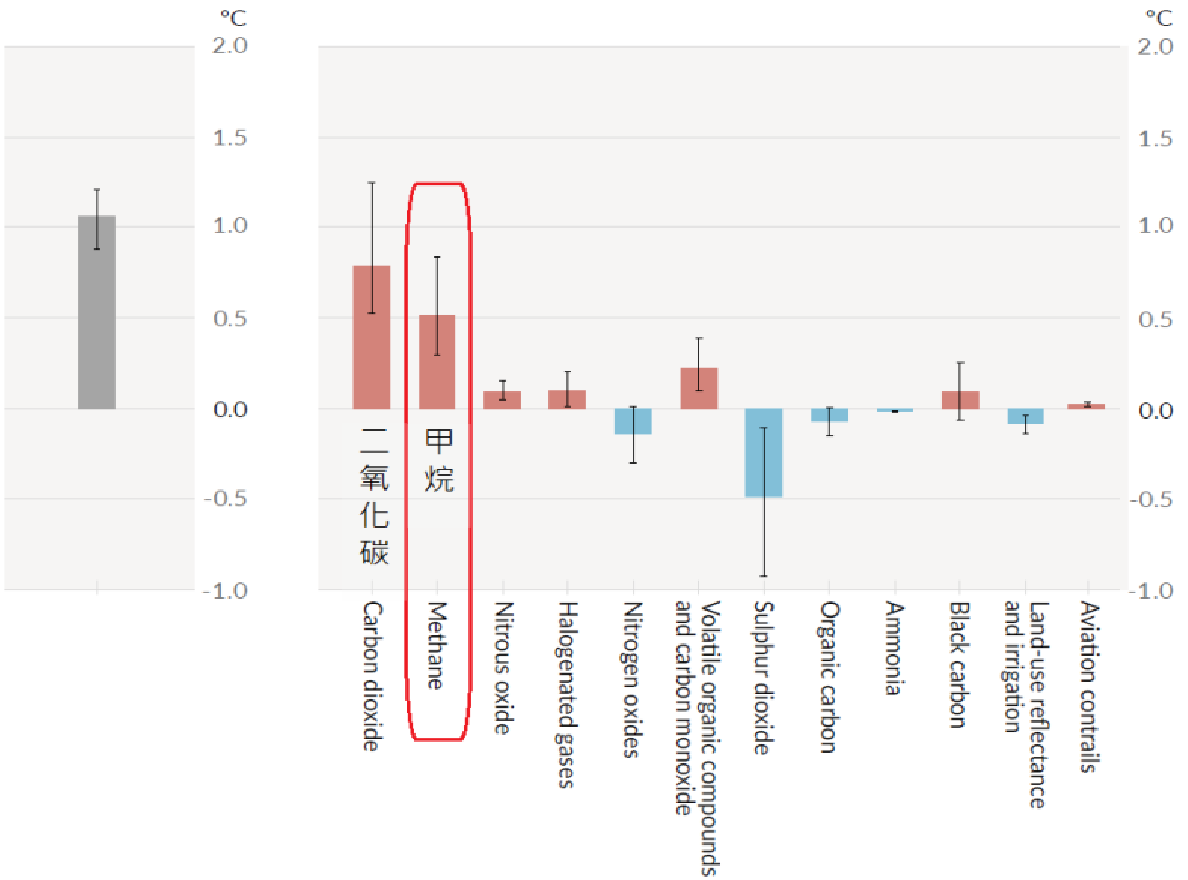
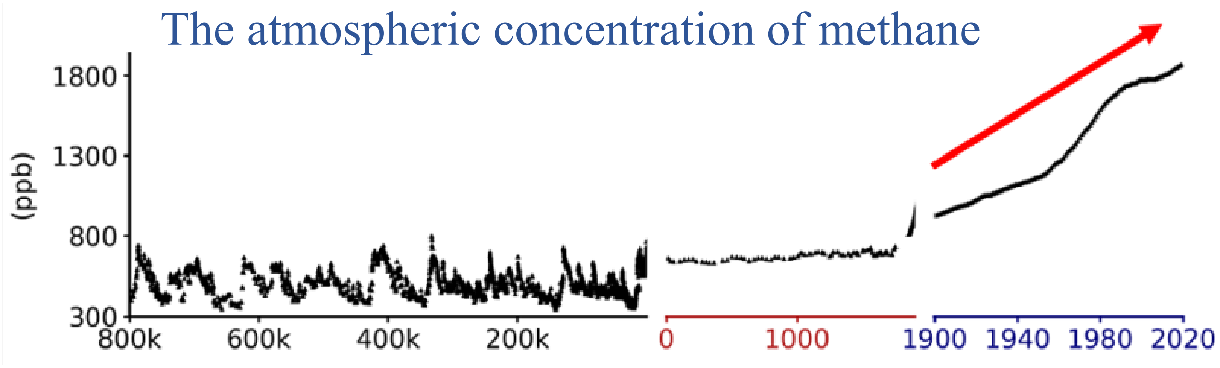
1. Introduction

- Methane (CH_4) possesses a higher global-warming potential compared to CO_2, up to 84 times as powerful as CO_2 over a 20-year time frame.
- CH_4 is responsible for around 30% of the observed global temperatures rise since the Industrial Revolution, making it the second-largest contributor after CO_2. Since the early 20th century, the atmospheric concentration of methane has been increasing rapidly and continuously.



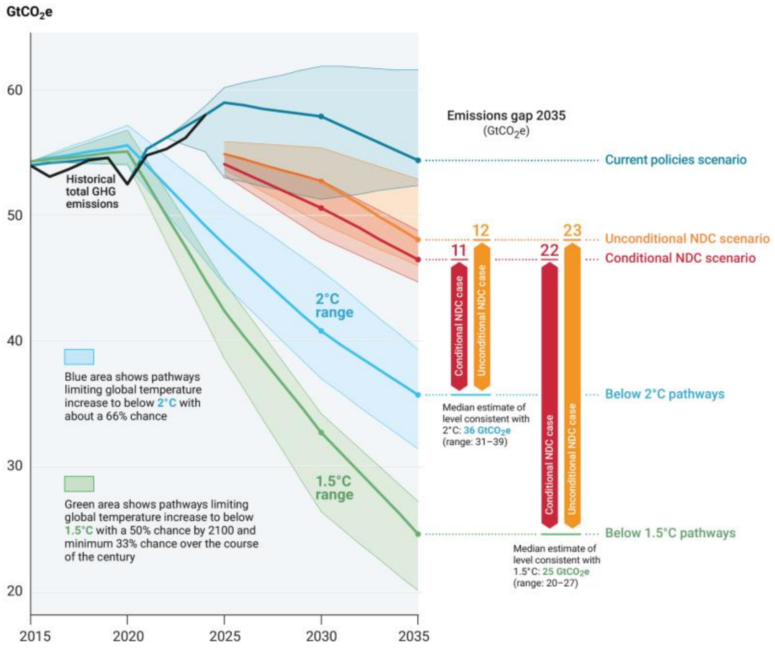
Global mean surface temperature anomaly in 2010–2019 relative to the 1850–1900 average (left) and the warming or cooling contributions from individual forcing agents (right). Source: IPCC AR6

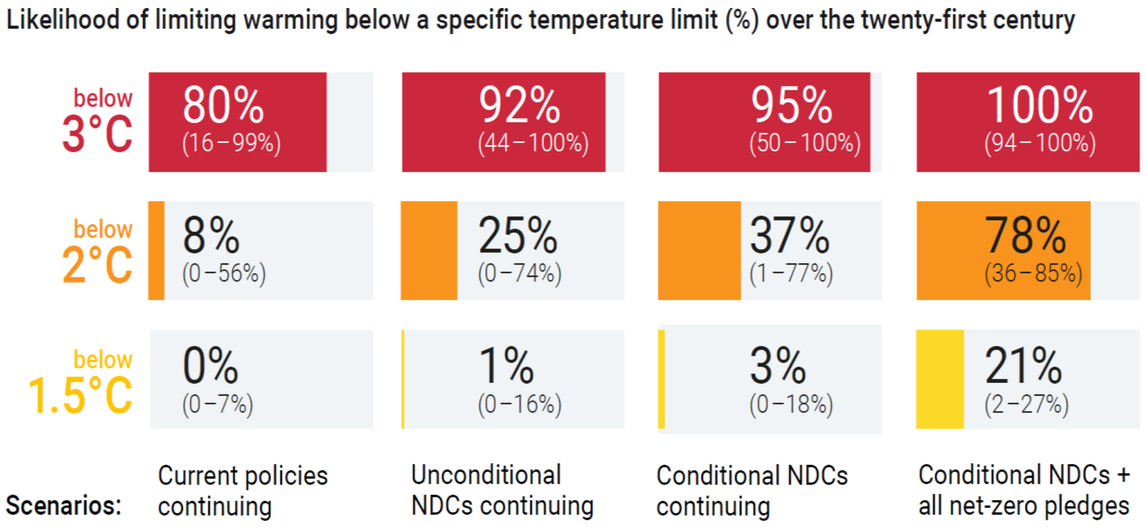


Source: IPCC AR6

There is an increasing recognition that rapid and sustained reductions in methane emissions are key to limiting near-term global warming and improving air quality (Global Methane Tracker, 2025).

Urgent action is required to bring methane back to a pathway more in line with **the Global Methane Pledge to reduce global methane emissions by at least 30% below 2020 levels by 2030** made at COP26 in 2021 .



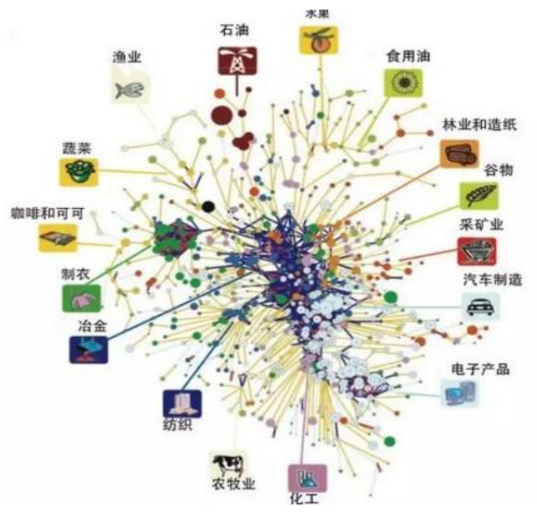


Source: UNEP(Emissions Gap Report 2025)

Obstacles to international cooperation toward achieving the Global Methane Pledge:

- Unclear pathways of methane emissions from economic activities and trade flows

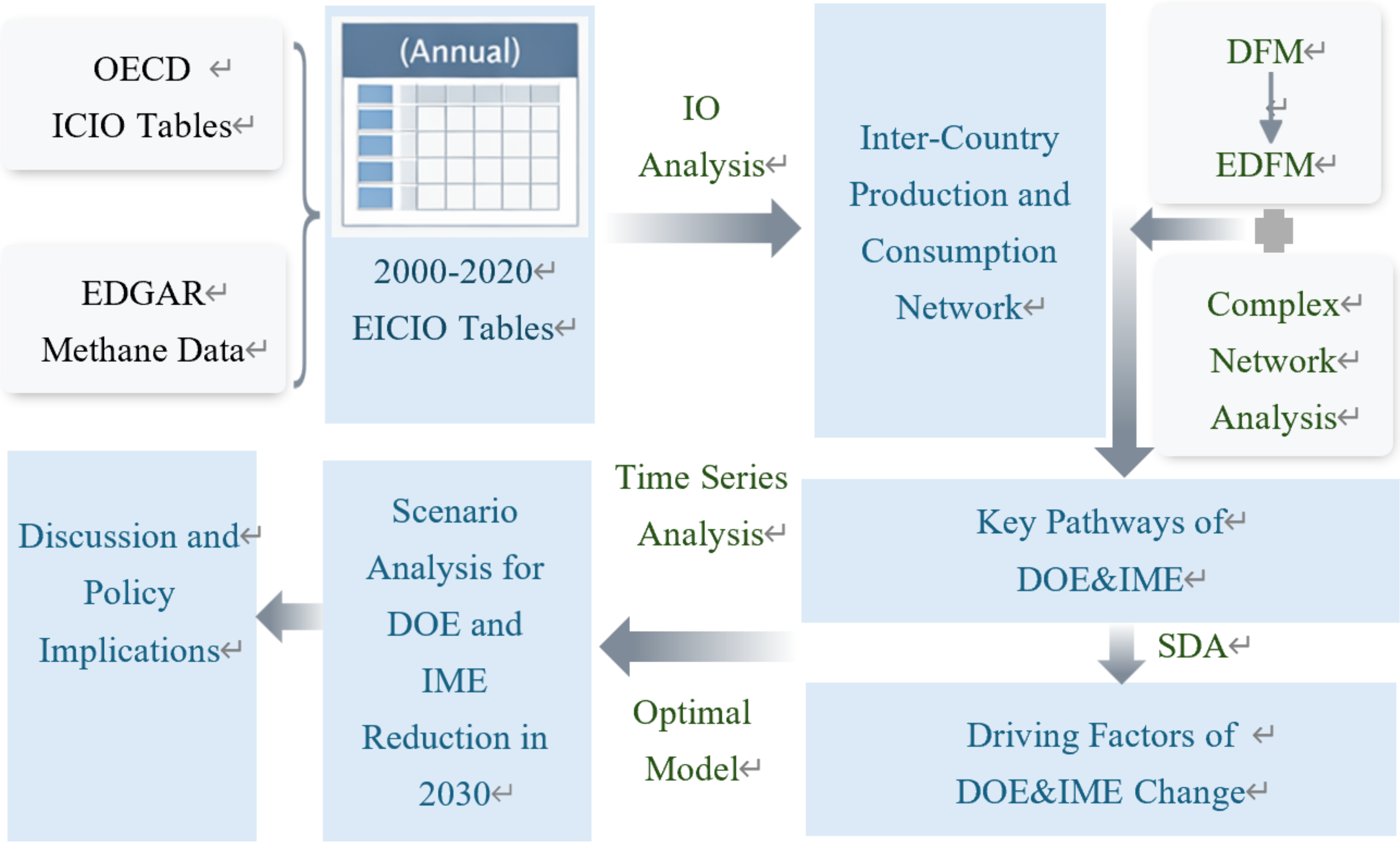
- Uncertainty regarding mitigation technologies and costs



Contributions of this paper

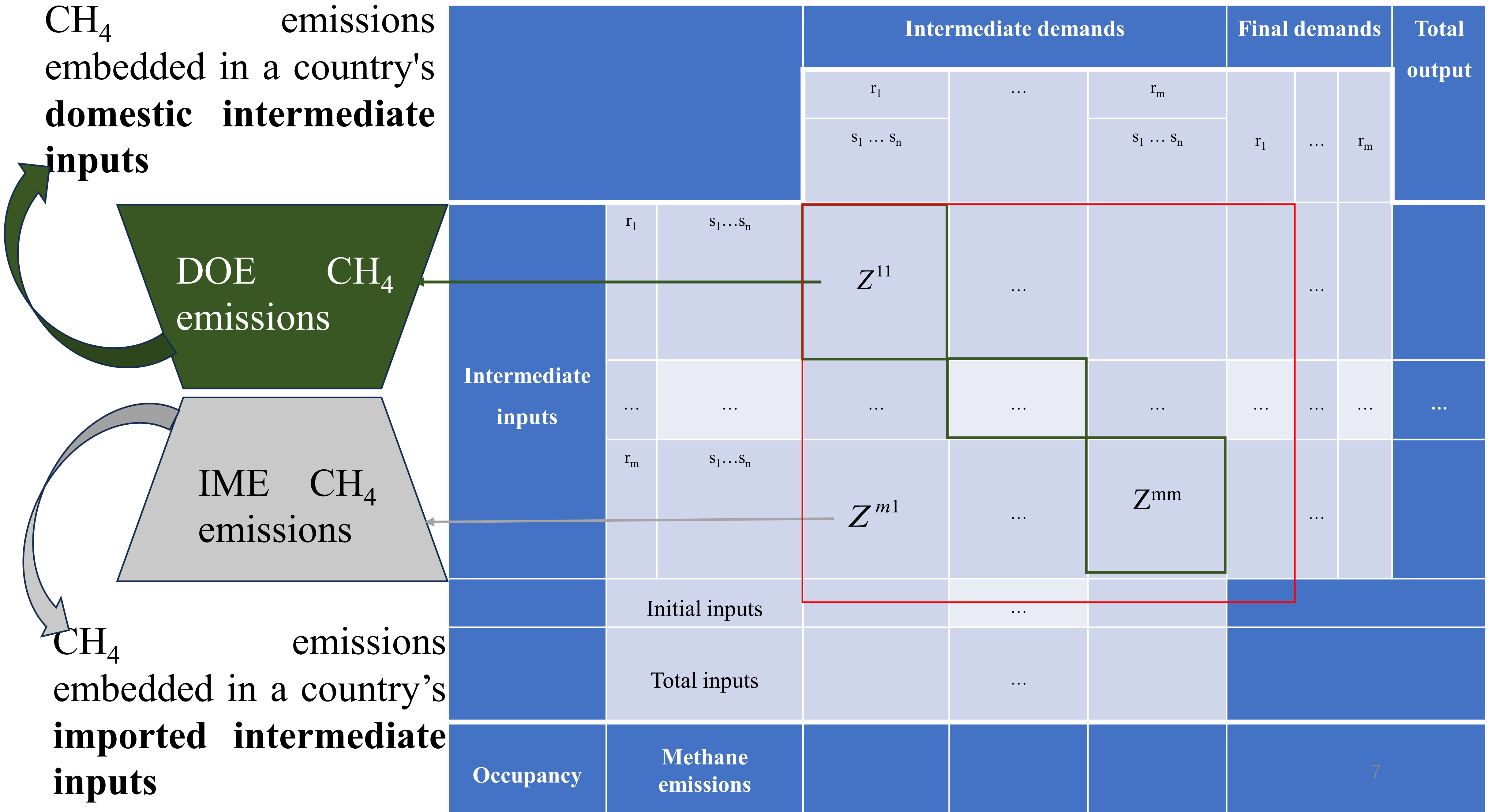
- The paper identifies the key pathways of embodied methane emissions within global production and consumption networks using an Environmental Double Filtering Method (EDFM) developed here.
- We separate embodied methane emissions into domestic (DOE) and imported (IME) types, and analyze the primary drivers of change for both DOE and IME across key linkages.
- More importantly, with an optimization model, we estimate the potential reduction volumes and minimum costs for DOE and IME at each key linkage using feasible technologies, thereby providing a strategic pathway to achieve the Global Methane Pledge by 2030.

2. Methodology



The flow chart of this study

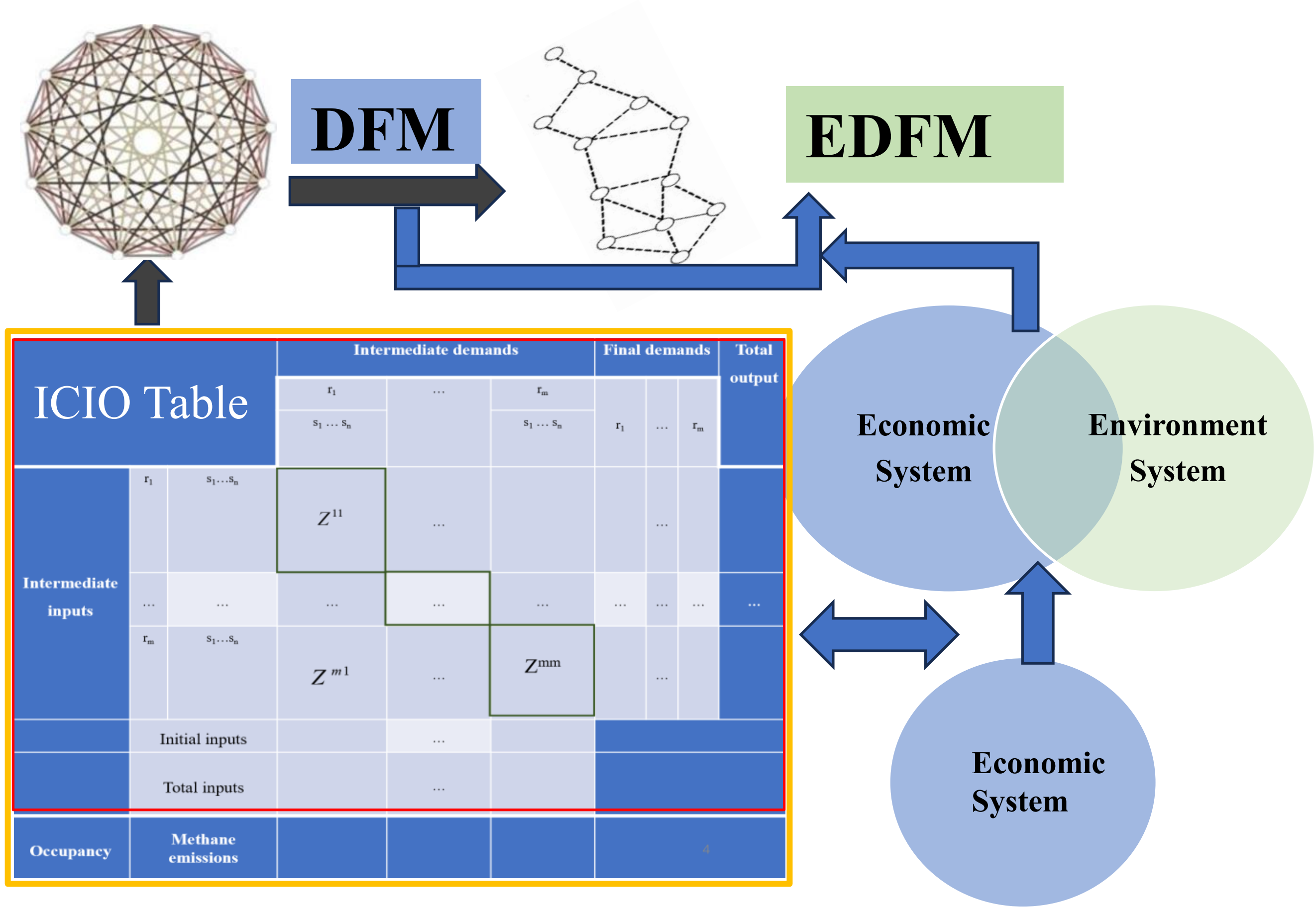
Environmental Inter-country Input-Output (EICIO) Table



Environmental double filtering method (EDFM)

EDFM is proposed to identify key pollutant emission pathways within complex economic-environmental systems. It is an extension of DFM method (Liu, 2018) in environment research.

The strength of the EDFM lies in its ability to identify key pathways from the perspective of inter-industry linkages, addressing the question of which specific economic activities, in which countries and sectors, drive how much methane emissions.



$$X_t = (I - A_t)^{-1} * F_t$$

$$Z_t = A_t *< X_t >$$

$$X_t = (I - A_t)^{-1} * F_t = \left(I + A_t + {A_t}^2 + {A_t}^3 + \cdots\right) * F_t$$

$$Z_t = A_t *< \left(I + A_t + {A_t}^2 + {A_t}^3 + \cdots\right) * F_t >= A_t *< F_t > + A_t *< A_t * F_t >$$

$$+ A_t *< (A_t)^2 * F_t > + \cdots$$

$$L_t^0 = A_t *< F_t >$$

$$L_t^h = A_t *< (A_t)^h * F_t > \; . . .$$

$$DME_{j,t}^s = \frac{ME_{j,t}^s}{xc_{j,t}^s}$$

$$DMEL_t^h = L_t^h *< DME_t >$$

$$TRME1_t = \frac{1}{k+1} * \sum_{h=0}^{k} \frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} DMEL_{i,j,t}^h$$

$$WME_{i,j,t}^h = \begin{cases} 1 & DMEL_{i,j,t}^h \geq TRME1_t \\ 0 & otherwise \end{cases}$$

$$EME_{i,j,t} = \sum_{h=0}^{k} WME_{i,j,t}^h / (k+1) \qquad \text{(h=0, 1, 2…k)}$$

$$TRME2_t = \frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} EME_{i,j,t}$$

…

3. Data Source

- The Inter-Country Input-Output (ICIO) Tables (OECD, 2024) and EDGAR 2024 (IEA, 2024) → **EICIO tables**
- Due to the various sector classification of ICIO and EDGAR v8.0, we have to merge the 23 methane sectors into 14 categories.

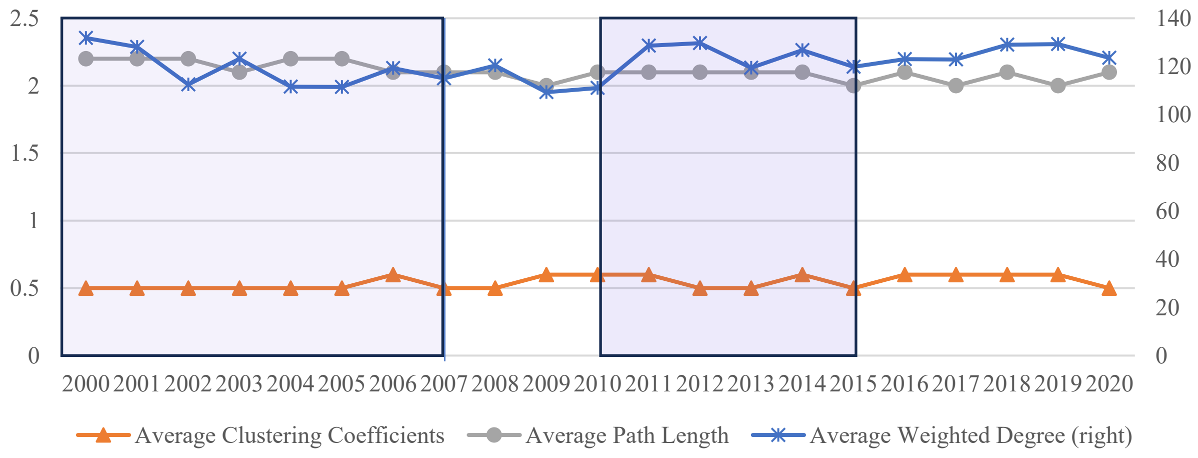
- 76 economies with 14 industries in each of the EICIO tables
- 38 OECD member countries and their major trading partners
- 2000-2020 annually

EICIO sector code and sector name

Sector Code	Sector Name
1	Electricity and Heat Production
2	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries
3	Manufacturing Industries and Construction, except Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries
4	Civil Aviation
5	Road and Rail Transportation
6	Water-borne Navigation
7	Other transportation
8	Solid Fuels, Oil and Natural Gas
9	Chemical Industry
10	Metal Industry
11	Enteric Fermentation, Manure Management, Emissions from biomass burning, Rice cultivations
12	Waste Treatment and Discharge, Residential and other sectors
13	Others
14	Household and Government Consumption

Phases segmentation of key pathways, 2000-2020

- With statistics test of the 2000-2020 time series of key pathways network indicator and climate change mitigation actions, we segmented the key pathways as follows: 2000-2007 (phase 1), 2008-2010 (phase 2), 2011-2015 (phase 3), 2016-2020 (phase 4).
- To optimize the use of annual data and to capture the distinct phase characteristics of the key pathways, we averaged the annual EICIO tables for the four phases, resulting in Phased-EICIO tables. We also applied the EDFM method to the 4 Phased-EICIO tables to identify the key pathways of embedded methane emissions at each phase and analyzed their changing characteristics.



4. Results

- The key pathways selected by EDFM is representative, whose CH_4 emissions amount accounted for more than 60% of the total CH_4 emissions with only around 0.24% of 1,132,096 sector linkages in each year from 2000 to 2020. The annual average number of linkages in the selected key pathways is 2,683, with a standard deviation of 59.

Sensitivity analysis of threshold TRME1

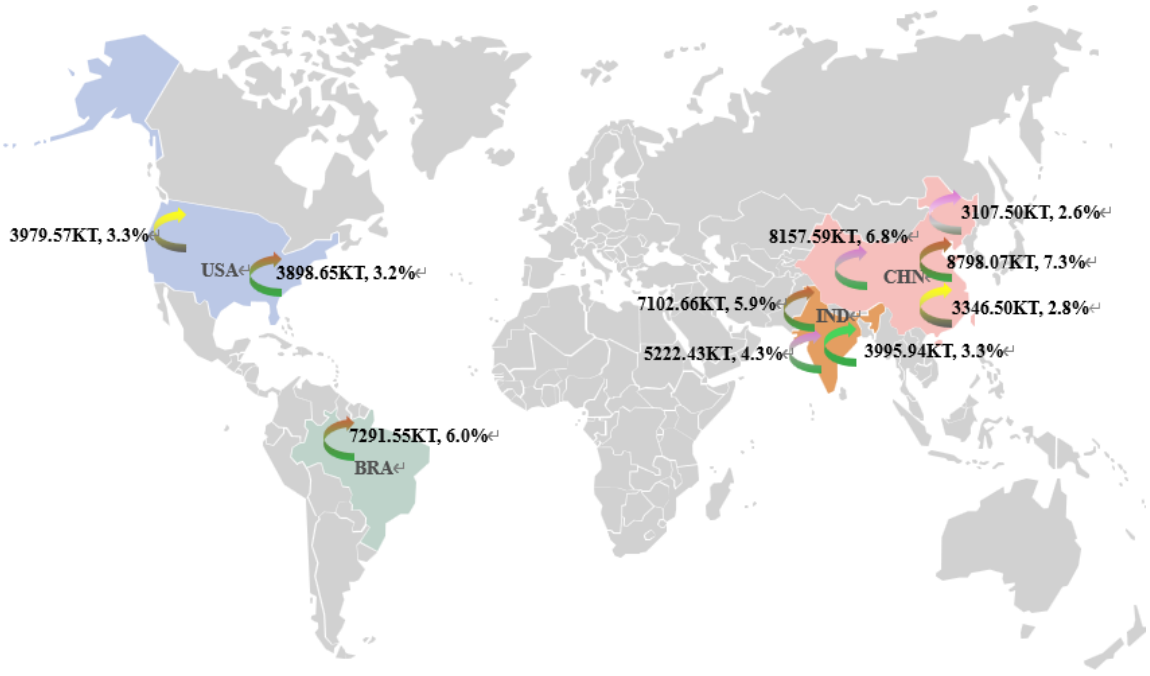
Phases	Threshold	The number of key linkages	The proportion of methane emissions embedded in key pathways
Phase1	1.532×10^{-5}	702	30.2%
	1.532×10^{-6}	2585	60.2%
	1.532×10^{-7}	80921	65.3%
Phase2	1.494×10^{-5}	568	28.7%
	1.494×10^{-6}	2667	61.6%
	1.494×10^{-7}	118879	67.6%
Phase3	1.681×10^{-5}	604	29.4%
	1.681×10^{-6}	2719	60.9%
	1.681×10^{-7}	99877	65.8%
Phase4	1.207×10^{-5}	833	32.4%
	1.207×10^{-6}	2771	60.1%
	1.207×10^{-7}	103206	68.5%

When the threshold is increased tenfold, the selected key linkages become unrepresentative: they identified fewer than 1000 key linkages, accounting for approximately 30% of methane emissions in the four phases. These comparisons demonstrate the effectiveness of the threshold setting in the EDFM method for selecting key pathways.
Furthermore, we found that the key pathways selected with the high threshold are all subsets of those selected with the low threshold, which is guaranteed by Equations (10) and (13). This also ensures the stability of the key pathway selection results obtained by the EDFM method.

Effectiveness comparison between the EDFM method and the traditional average value method (AVM)

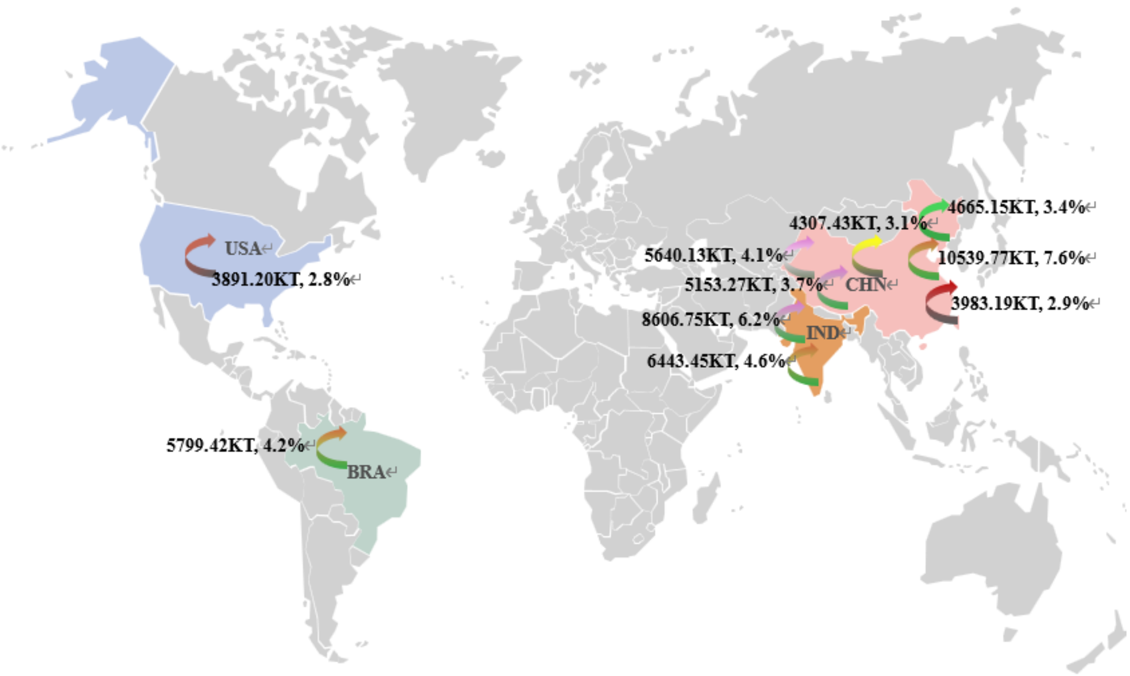
Phases	methods	The number of key linkages	The proportion of methane emissions embedded in key pathways
Phase1	EDFM	2585	60.2%
	AVM	503055	92.9%
Phase2	EDFM	2667	61.6%
	AVM	502571	92.4%
Phase3	EDFM	2719	60.9%
	AVM	504553	92.6%
Phase4	EDFM	2771	60.1%
	AVM	505651	92.3%

4.1 DOE CH_4 emissions



(1a) phase1

Waste → Household Consumption
Agriculture → Other Manufacturing and Construction
Agriculture → Agriculture
Primary Energy → Petroleum Refining
Agriculture → Household Consumption



(1d) phase4

Waste → Household Consumption
Agriculture → Other Manufacturing and Construction
Agriculture → Household Consumption
Agriculture → Agriculture
Primary Energy → Metal Industry
Primary Energy → Petroleum Refining

Top 10 linkages by DOE (unit: KT) in key pathways across phases

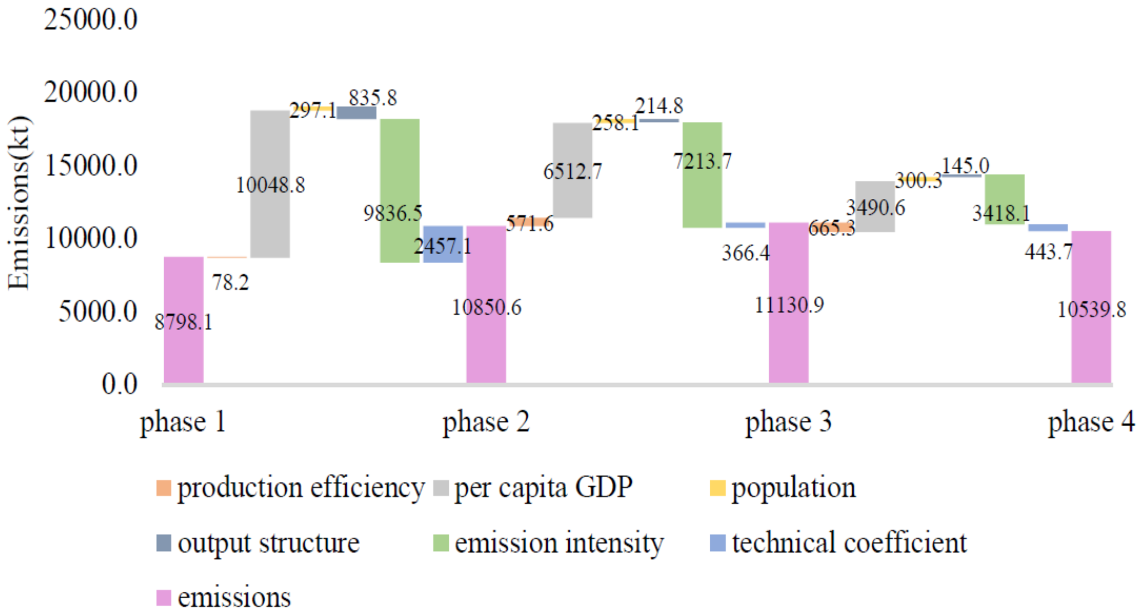
DOE Results Analysis

- **The sum of the DOE in the top 10 linkages account for around 45% of total DOE in the key pathways for each phase**.
- These linkages were predominantly found in India, China, the United States, and Brazil, with the primary flows originating from the Agriculture, Primary Energy, and Waste sectors to Other Manufacturing and Construction, Consumption, Petroleum Refining, and Metal Industry sectors.
- Top two linkages throughout the four phases :

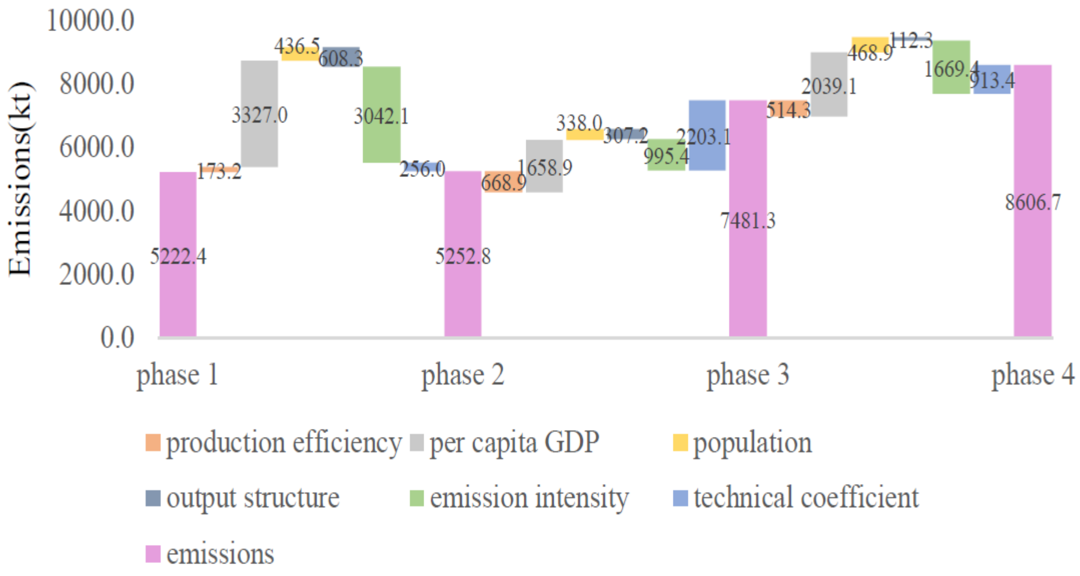
(China, Agriculture) → (China, Other Manufacturing and Construction)

(India, Agriculture) → (India, Consumption)

- From phase 1 to phase 4, the names and rankings of the top 10 DOE linkages exhibited only a few changes

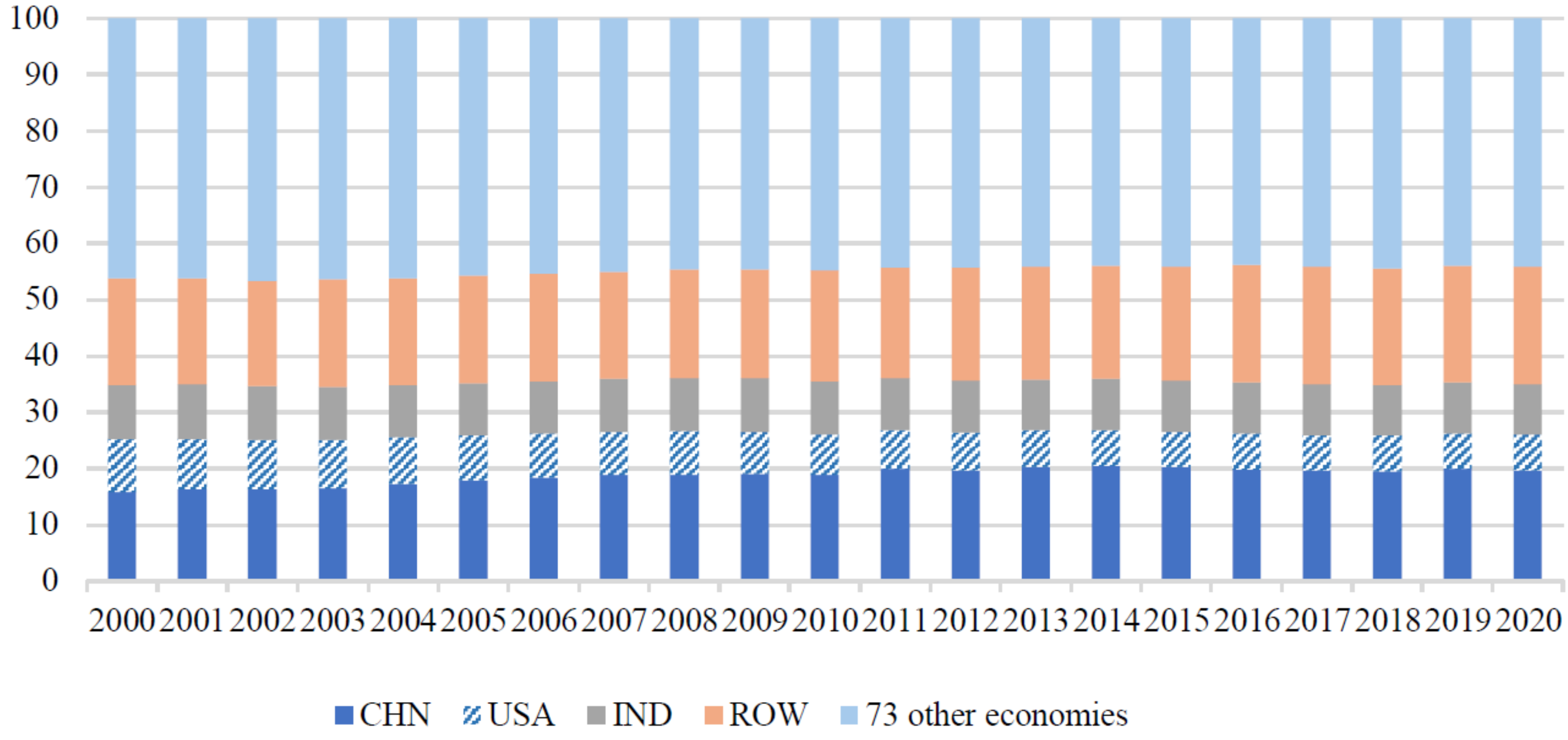


SDA results of (CHN, Agriculture) → (CHN, Other Manufacturing and Construction)

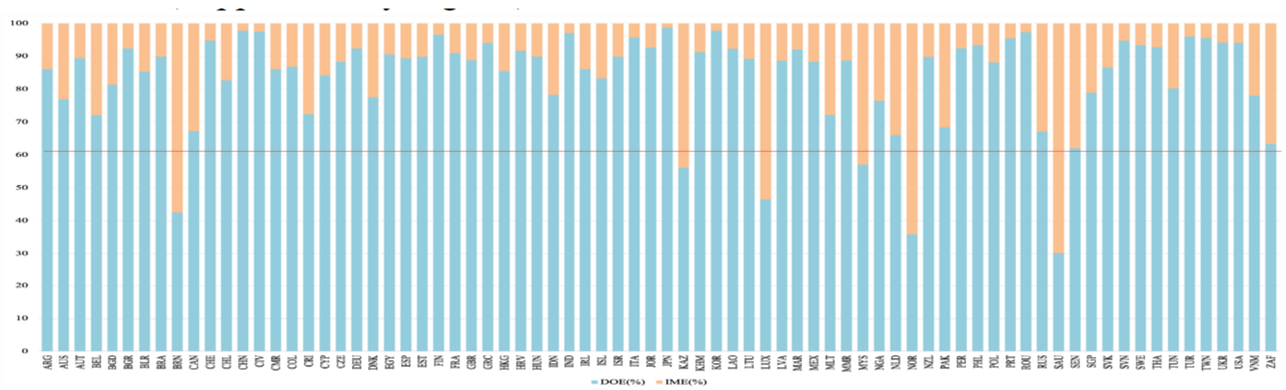


SDA results of (IND, Agriculture) → (IND, Consumption)

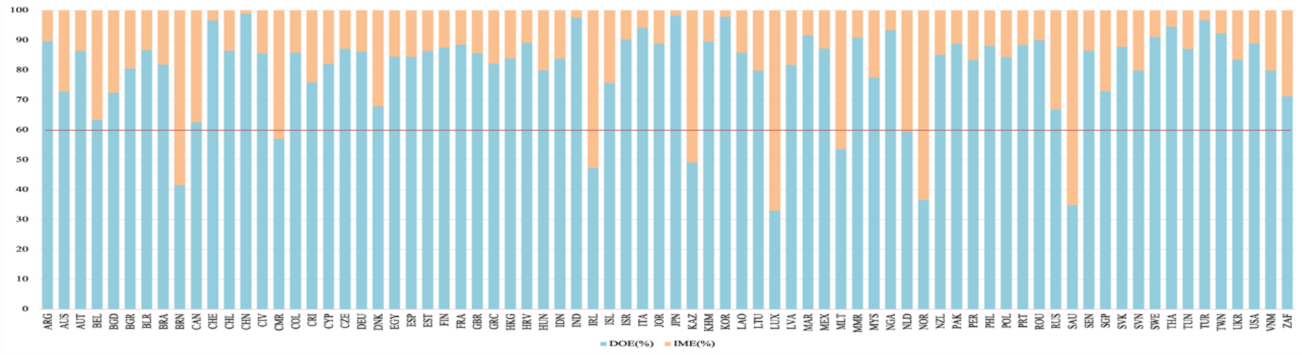
Note: In above figures, the number on each red column indicates the DOE of the linkage for each phase as specified in the subtitle, while the numbers between columns denote the contributions of six impacting factors to the reduction in the DOE between consecutive phases.



Proportional distribution of global DOE: contributions from CHN, USA, IND, ROW (rest of the world), and 73 other economies



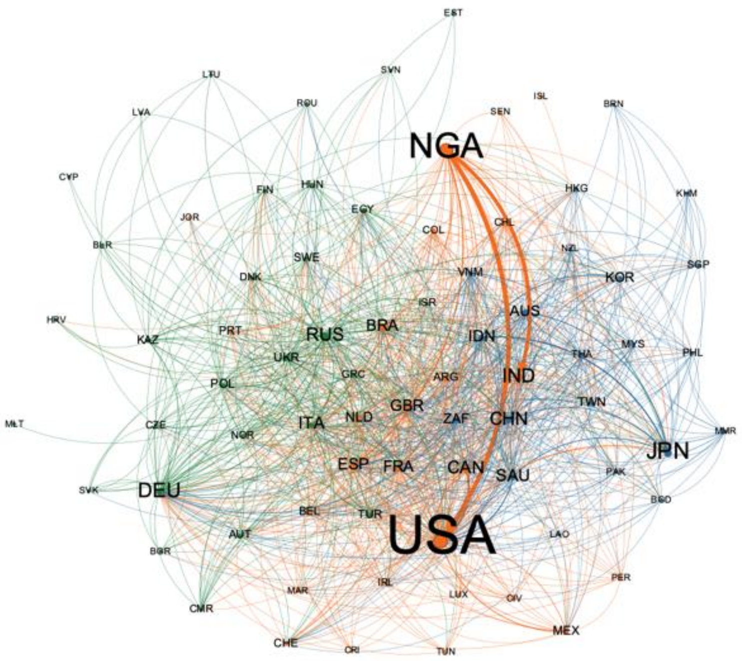
Phase 1



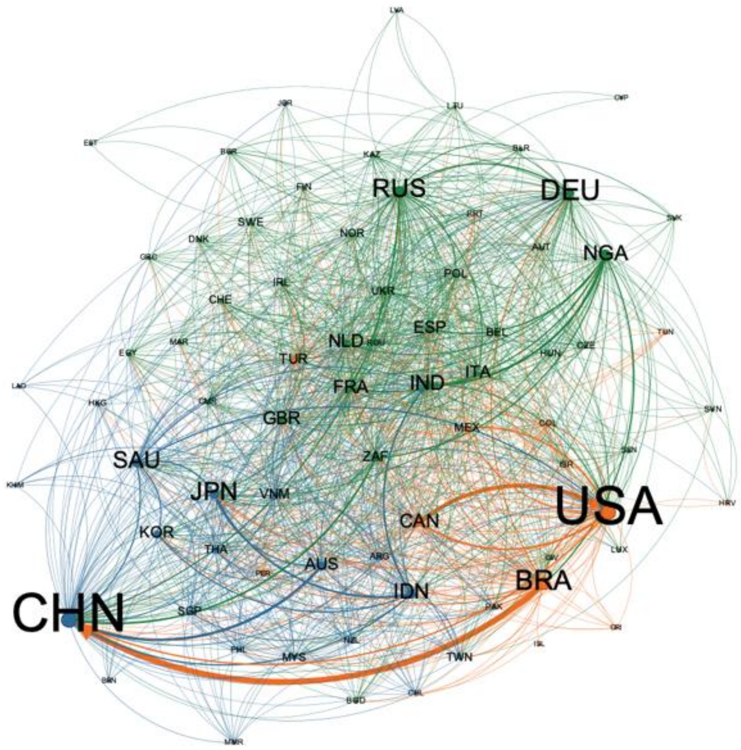
Phase 4

The figure shows that the majority of the 76 economies had average domestic (DOE) share of national methane emissions exceeding 60% each year with imported emissions as the remainder, a trend that had been consistent across the 4 phases.

4.2 IME CH_4 emissions

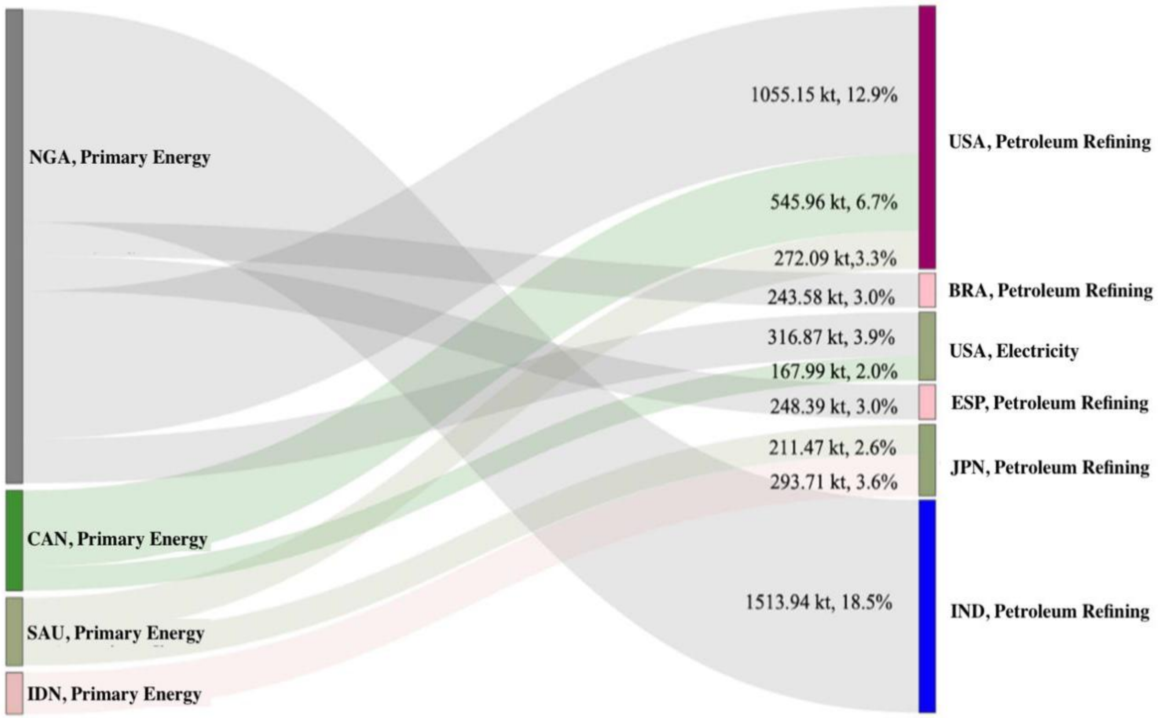


Phase 1

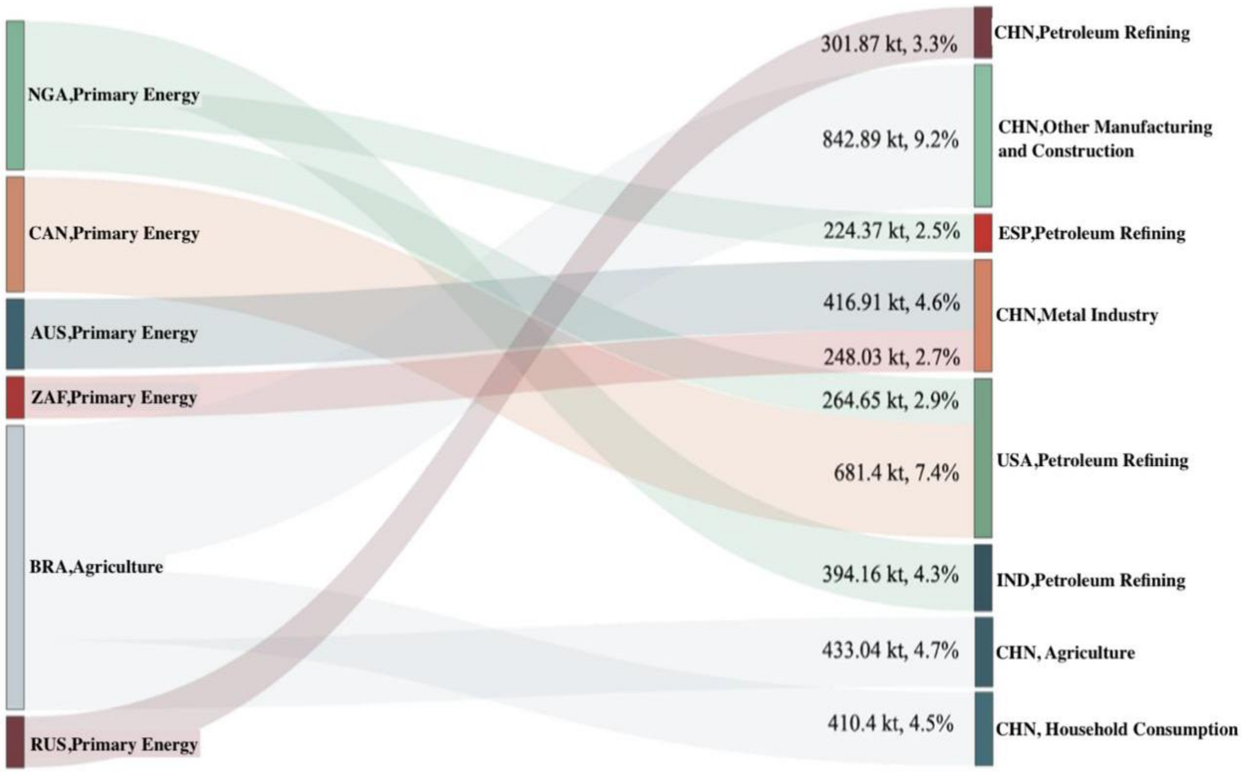


Phase 4

Network combined by key pathways of IME among economies by phase



Phase 1

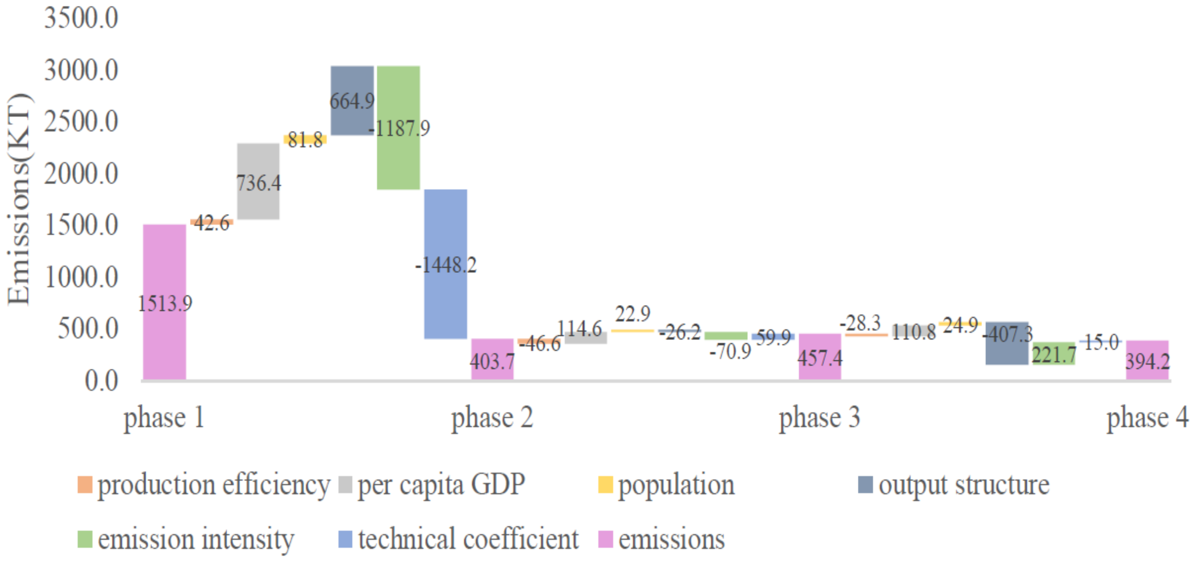


Phase 4

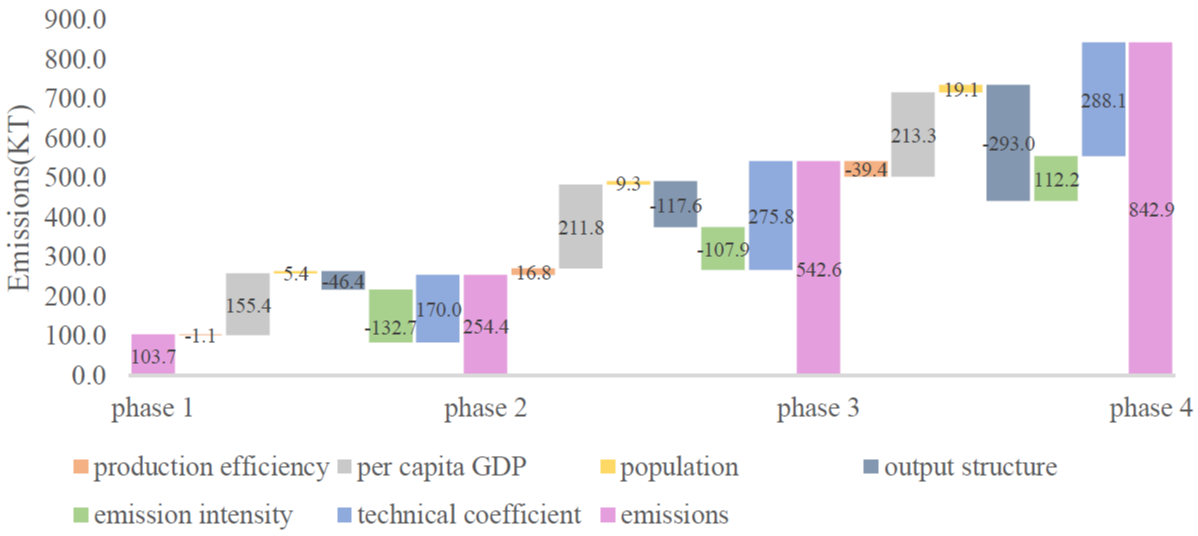
Top 10 linkages by IME (unit: KT) in the key pathways across phases

IME Results Analysis

- The key pathways of IME established emission communities with hub economies such as the USA, Russia and China at different stages.
- In the first stage, three emission communities were formed and centered around USA, Russia (RUS) and Japan (JPN).
- In phase 4, except China, Brazil (BRA) gradually took the outstanding position in the orange community, whose fourth phase IME accounting for 32.46% of the community’s IME. Conversely, the hub economy Germany in the European community experienced a 21.2% decrease in the IME by the fourth phase compared with the third phase.



The decomposition of (NGA, Primary Energy) → (IND, Petroleum Refining)



The decomposition of (BRA, Agriculture) → (CHN, Other Manufacturing and Construction)

4.3 Scenario analysis of DOE and IME reduction by 2030 under technical applicability and minimum cost constraints

We predicted the methane emission intensity decrease (Table 3) and technological coefficients improvement of the input sectors in the key pathways in 2030, we estimated the methane mitigation potential through key pathways under scenario 1 (methane emission intensity reduction) and scenario 2 (technical coefficient improvement) in 2030.

The reduction of DOE and IME in key linkages and corresponding cost in scenario 1 by emission intensity reduction

Origins	Targets	Emission Intensity in 2020	Predicted Emission Intensity in 2030	DOE/IME Reduction (KT)	Cost (billion $)
DOE related results					
('CHN', '11')	('CHN', '3')	0.0102	0.0017	8216.73	0.89
('IND', '11')	('IND', '14')	0.0362	0.0131	5872.72	0.58
('CHN', '12')	('CHN', '14')	0.0015	0.0002	5113.69	7.17
('CHN', '8')	('CHN', '2')	0.0203	0.0044	4578.19	0.33

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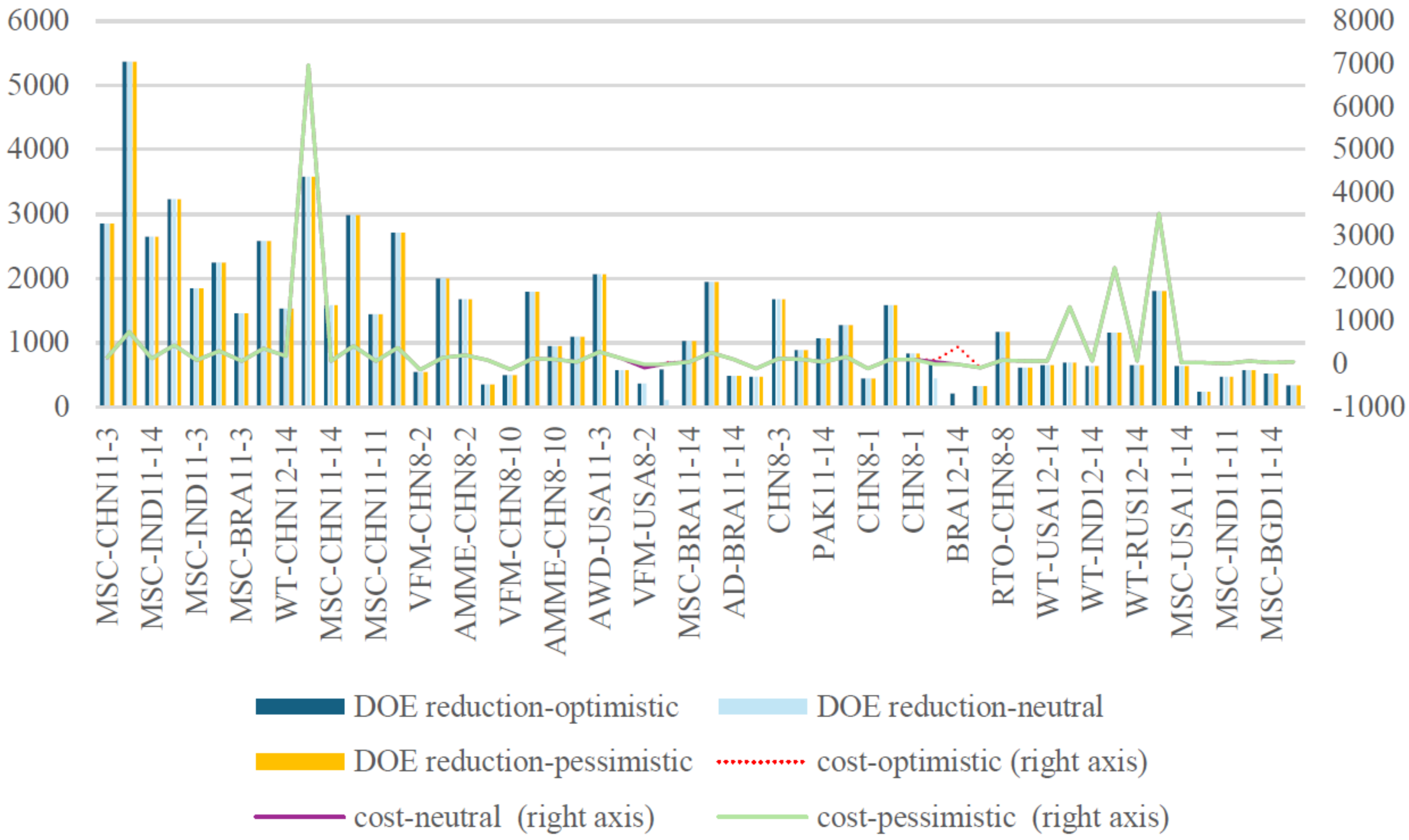
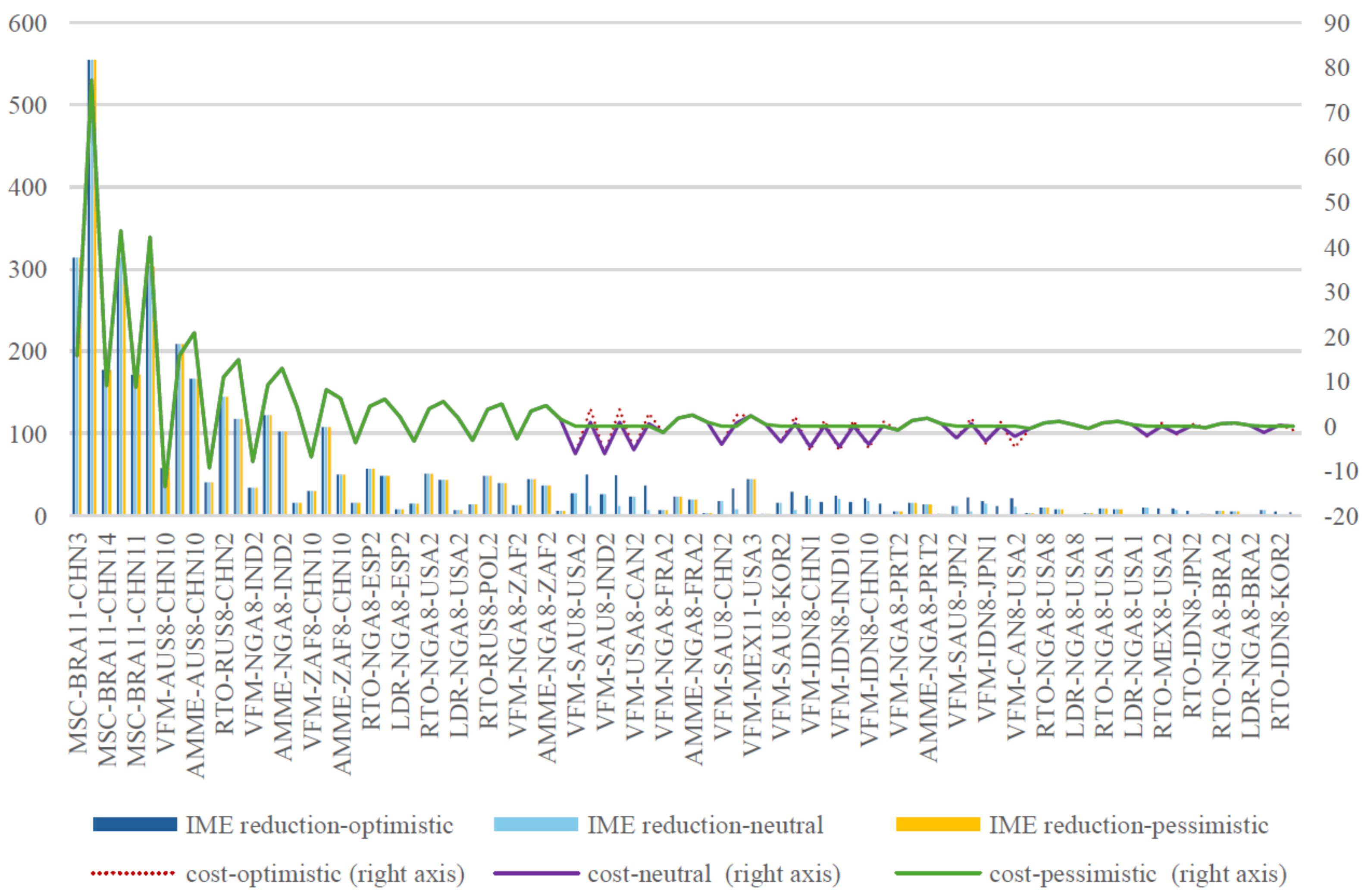


Feasible technologies, DOE reduction (unit: kt), and costs (unit: million \$) for DOE-based key linkages in scenario 1 in three cases

Note: In this figure, MSC-CHN 11-3 denotes the key linkage from Sector 11 to Sector 3 in China is matched with MSC (Manure Storage Covers) technology. All other symbols on the x-axis follow the same naming rule.



Feasible technologies, IME reduction (unit: kt), and costs (unit: million $) for IME-based key linkages in scenario 1 in three cases

Findings in Scenario 1

- In Scenario 1, **the combined reduction of DOE and IME in the key linkages identified represents 30.7% of global methane emissions recorded in 2020**, indicating that the Global Methane Pledge by 2030 can be achieved.
- Based on literatures review of methane emission reduction technologies widely applied up to 2025, we proposed detailed technological measures to reduce methane emission intensity for each key linkage's origin sector with optimal method. Under these measures, **the minimum total cost for achieving the emission reductions in Scenario 1 is estimated to be US$20.63 billion.**
- **The cost distribution is primarily concentrated** in DOE emissions from Sector 11 (Agriculture) in China (CHN), Brazil (BRA), Pakistan (PAK), and Bangladesh (BGD); DOE from Sector 12 (Waste) in Russia (RUS), India (IND), and China (CHN); and IME from Sector 8 (Primary Energy) in Nigeria (NGA), Australia (AUS), and South Africa (ZAF).
- **In contrast, negative abatement costs are predominantly observed in** DOE from Sector 8 (Primary Energy) in USA and IME from Sector 8 (Primary Energy) in Indonesia (IDN), Saudi Arabia (SAU), Canada (CAN), the United States (USA), and Mexico (MEX).
- These findings provide a practical pathway to achieve the Global Methane Pledge by 2030 through targeted interventions in the key linkages outlined in this study.

Scenario 2: Technical Coefficient Improvement

- The total reduction in DOE and IME emissions under scenario 2 amounts to 8,858.31 KT, constituting 4.5% of the global methane emissions in 2020.
- **In comparison, the combined reduction in DOE and IME across all key linkages in scenario 2 is substantially lower than that projected in scenario 1, with a shortfall of 66,907.72 KT.**
- **This marked difference underscores the critical importance of prioritizing the mitigation pathways outlined in scenario 1 to effectively fulfill the global commitment to reducing methane emissions.**

5. Conclusions

- This research developed an approach known as EDFM to identify key pathways within the intra-country and inter-country production networks that contribute the most to CH_4 emissions during the world production process.
- **In contrast to previous studies**, this research identified key pathways within intra-country and inter-country production and consumption networks across 76 main economies worldwide and their 14 industries, provided a potential way with emission intensity decrease through key pathways in scenario 1 to achieve the Global Methane Plague by 2030, reducing methane emissions 30.7% compared to 2020 level with the cost US$20.63 billion.
- Naturally, the proposed solution in this study is also applicable to the mitigation of other kind of greenhouse gas emissions.

6. Limitations and future research directions

- The low resolution of agricultural, coal mining industry etc. could cause uncertainty to the global analysis.
- The holistic analysis in this study lays the foundation for future studies, which will zoom in on specific industries within these pathways, such as Primary Energy and Waste Treatment.
- A more granular analysis will provide valuable insights into mitigation measures for the individual sector.

Thanks.

Your questions or suggestions please.

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