



清华大学深圳国际研究生院
Tsinghua Shenzhen International Graduate School

The 1st IEEE PES International Meeting
Hong Kong SAR, China, January 21, 2026



Power & Energy Society®
INTERNATIONAL MEETING
2026

Offshore Energy Internet: Wind-powered Green Hydrogen and Energy Islands

Xinwei Shen

Tsinghua Shenzhen International Graduate School



Report Outline

01 Background

02 Methodology

03 Results Analysis

04 Related Research



Report Outline

01 Background

02 Methodology

03 Results Analysis

04 Related Research

Climate change incentives



- 《2030 Carbon peak action plan》, 《2024 Energy work guidelines》 etc
- Coordinate and optimize the offshore wind layout, promote the construction of offshore wind bases.

Large capacity and scalability



- **8~14MW** offshore wind turbines have been applied.
- **16+ MW** have also been released.
- **Over 1 Trillion USD** will flow into the global offshore wind industry before 2035.

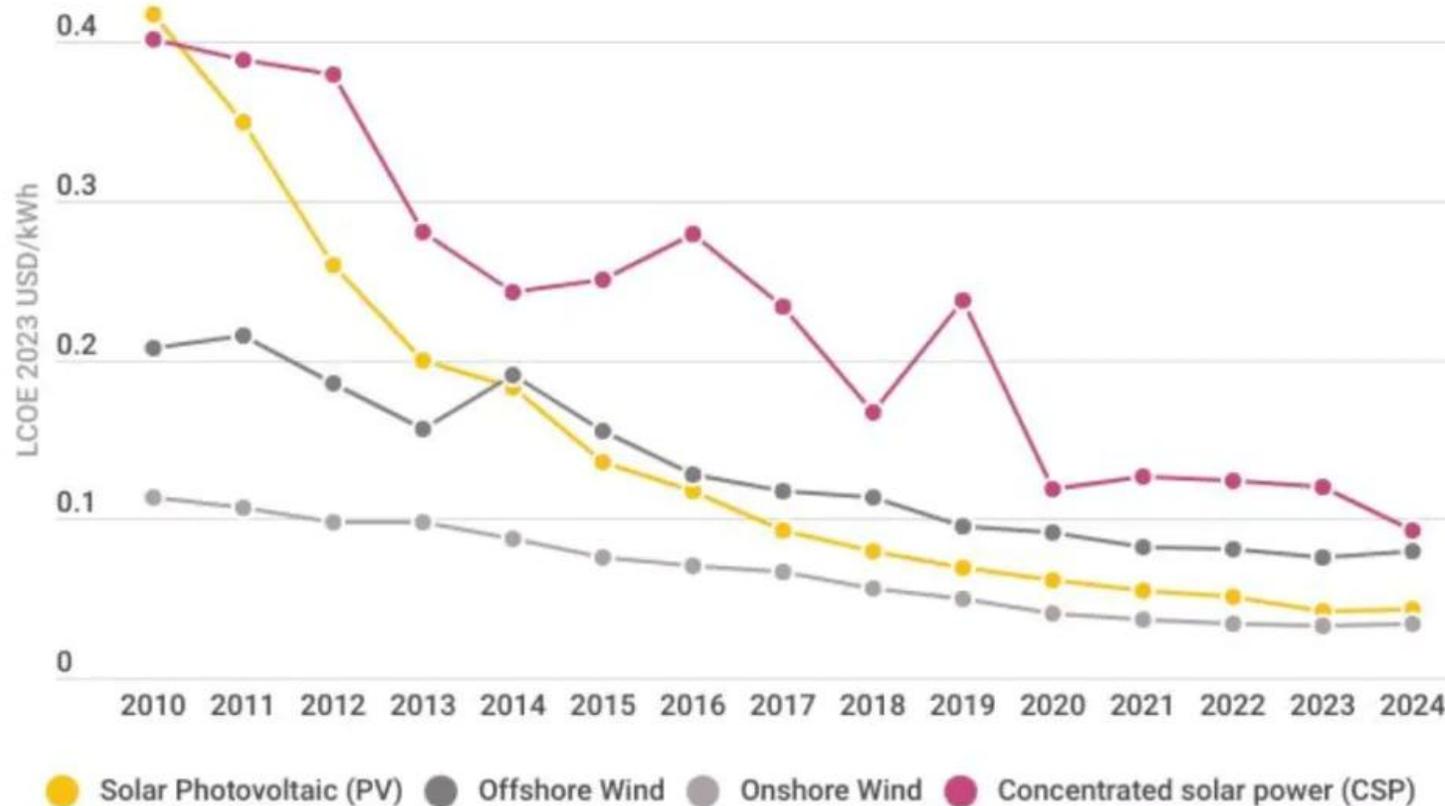
Hydrogen production



- Intermittency and volatility of wind power affect the **safe and stable operation** of power grid
- **Hydrogen production** becomes the preferred solution for far-offshore wind power development

The offshore wind powered-hydrogen production has great potential!

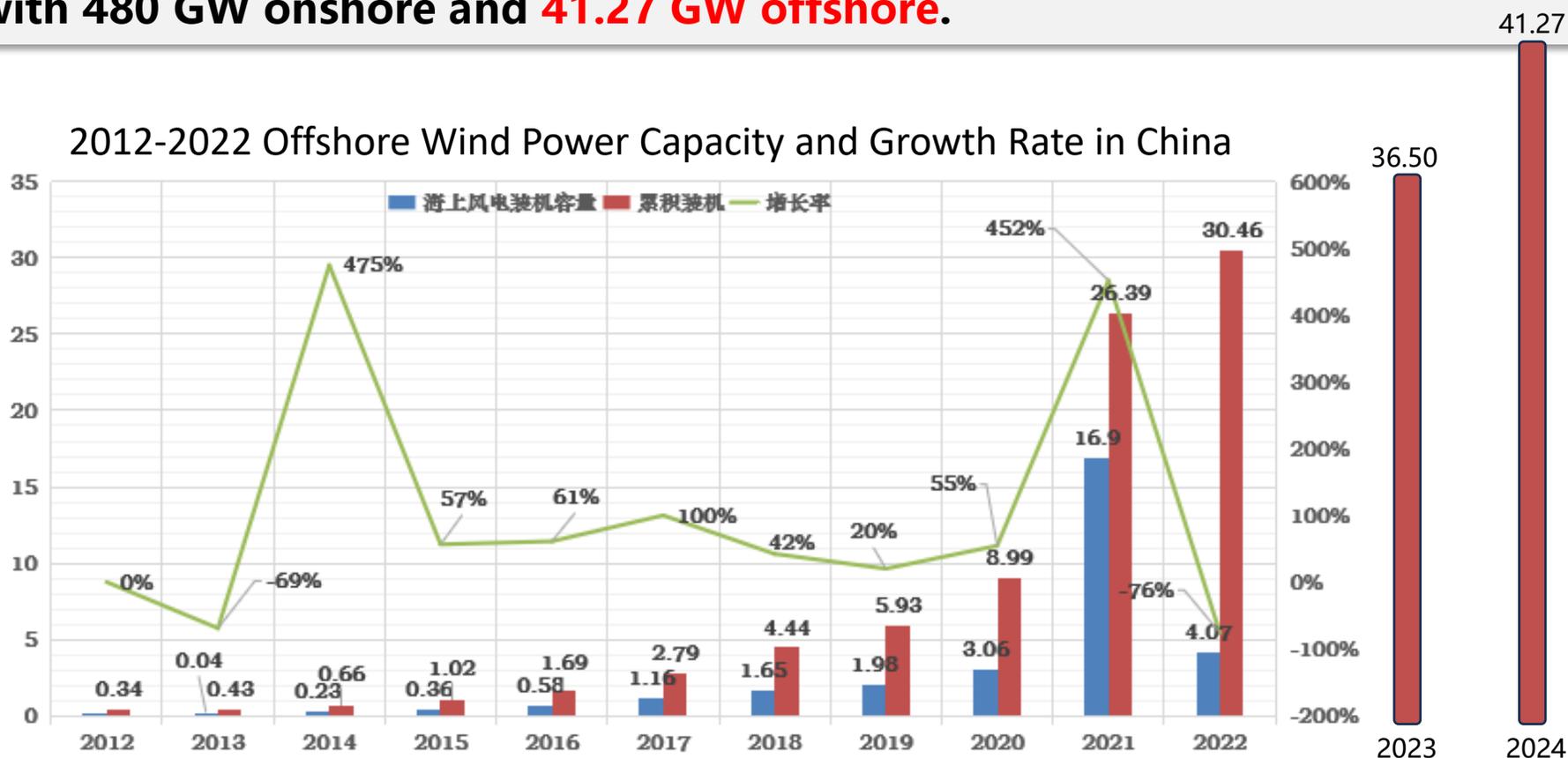
- ❑ Significant efforts have been made to drive cost reduction, enhance performance, and accelerate the large-scale deployment of offshore wind power worldwide.
- ❑ “The cost-competitiveness of renewables is today’ s reality...the avoided fossil fuel costs in 2024 reached up to \$ 467 Bn. ”——Francesco La Camera, Director-General of IRENA



LCOE trends of various renewables over the past few years

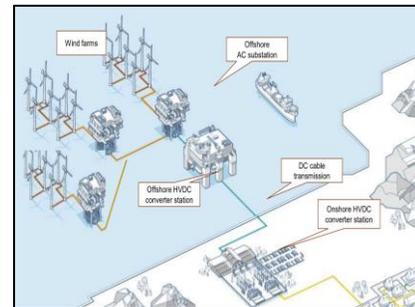
Advancement of the Offshore Wind Power in China:

- China added 79.82 GW of new wind power capacity in 2024, marking a 6% annual increase, including 75.79 GW onshore and **4.04 GW offshore**.
- The cumulative grid-connected wind power reached 521 GW, an 18% increase compared to 2023, with 480 GW onshore and **41.27 GW offshore**.





<p>MRE such as Offshore Wind, Wave, Tidal etc to generate clean power as a foundation for far-offshore deep sea development and utilization</p>	<p>P2X tech. to convert surplus MRE into high-energy-density fuels, facilitates the efficient integration and flexible utilization of MRE</p>	<p>HVDC/AC, LFAC + gas pipes + shipping etc as energy transmission/transportation network</p>	<p>Large-scale energy/hydrogen storage systems to smooth the fluctuations of MRE</p>	<p>Island microgrid and oil&gas platforms, with CCUS, to promote low-carbon and eco. usage</p>
--	--	--	---	---



Energy Islands will reshape the MRE development, providing a green, efficient and close-loop solution

Natural energy islands:

- Easy to implement;
- Geographical Feasibility as a energy hub

Grid-connected natural energy islands



Bornholm Energy Island, Denmark

Grid-connected energy islands:

- Connection with onshore power system;
- Higher flexibility and stability

Off-grid natural energy islands



Changdao Zero-carbon Energy Island, China

Off-grid energy islands:

- independent system;
- Flexibility and stability issues

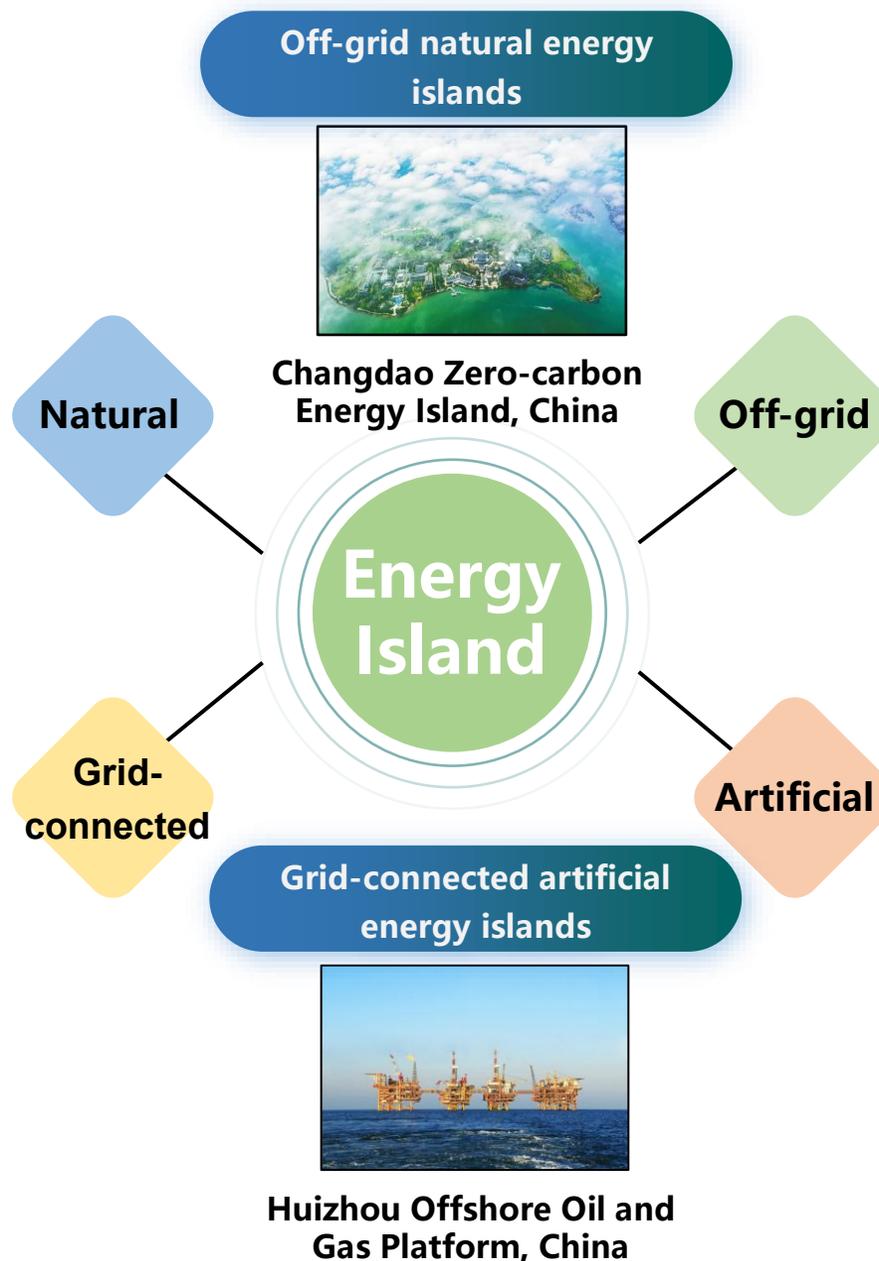
Off-grid artificial energy islands



"Deep Sea No.1", China

Artificial energy islands:

- Oil and Gas Platform;
- Special operation conditions;
- Integrated energy system



Huizhou Offshore Oil and Gas Platform, China



Ship carrying Hydrogen



**“COSCO SHIPPING YANGPU” (2025)
First Ship using Methanol as fuel in China**

“Hydrogen”

- H₂
- Methane
- Methanol
- Ammonia

● Black Hydrogen

Produced from coal

● Grey Hydrogen

Produced from Oil and Gas

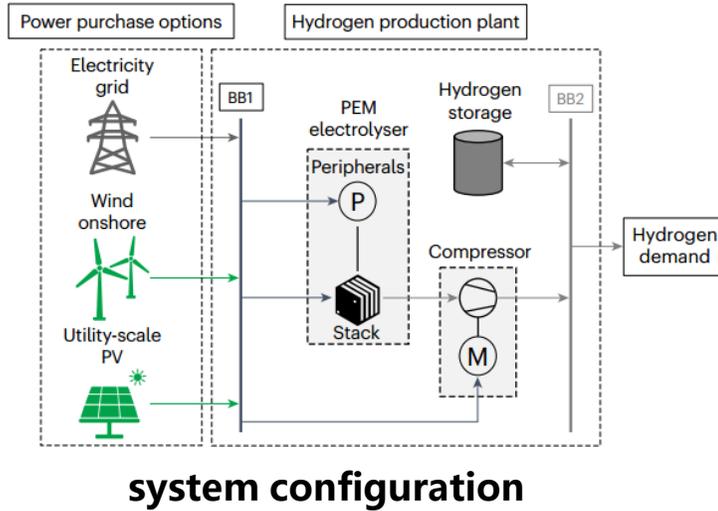
● Blue Hydrogen

From Oil and Gas but with CCUS

● Green Hydrogen

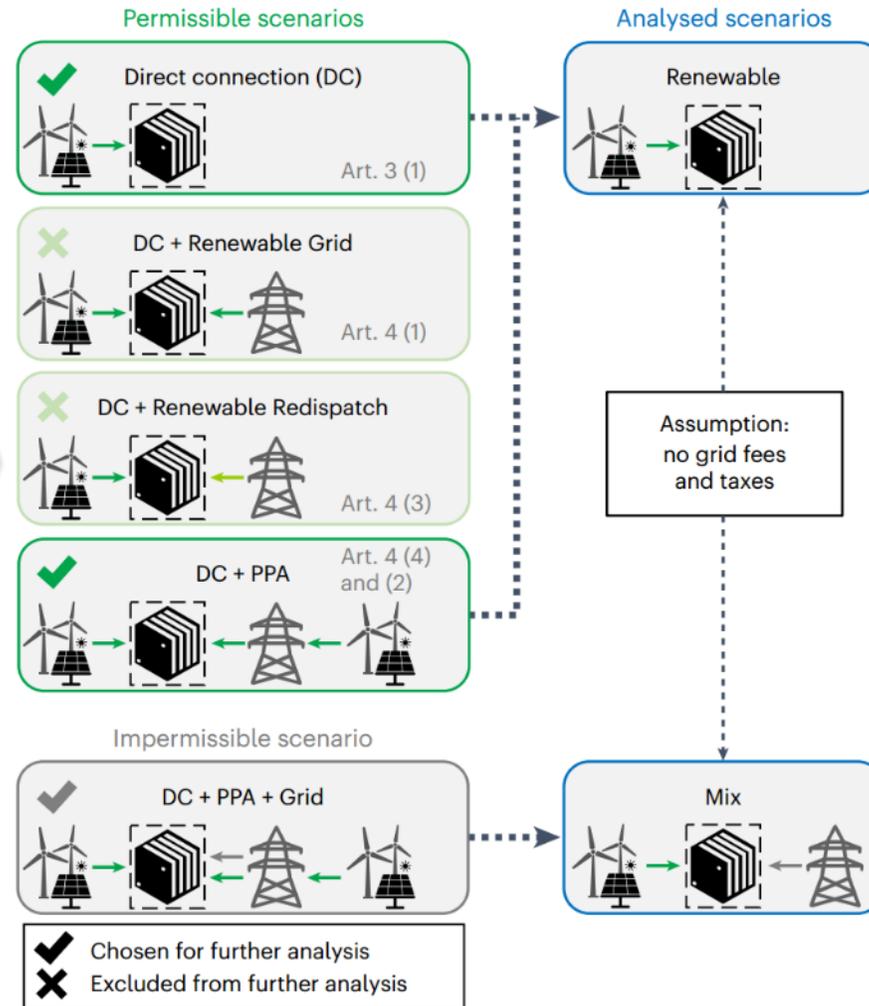
Produced From renewable energy

EU Regulations define “green”, which affects production system configuration significantly^[1]



“Green hydrogen” scenario:

- Direct connection (DC)
- Grid power with renewable > 90%
- Grid power after signing a renewable power purchase agreement (PPA).



Scenario design based on EU Renewable Energy Directive (RED)

Additional constraints

- Balance scenario constraints
- power of electrolytic system \leq the renewable power.

$$\sum_{t=k \times 730 + 1}^{(k+1) \times 730} (P_{ElySys,t}) - \sum_{t=k \times 730 + 1}^{(k+1) \times 730} (P_{nom,WT} \times p_{WT,t} + P_{nom,PV} \times p_{PV,t}) \leq 0 \quad \forall k \in \{0, 1, 2, \dots, 11\}$$

- Renewable share scenario constraints
- 90% of the total power of the electrolytic system \leq the potential renewable power.

$$\sum_{t=1}^T (P_{ElySys,t}) \times 0.9 - \sum_{t=1}^T (P_{nom,WT} \times p_{WT,t} + P_{nom,PV} \times p_{PV,t}) \leq 0$$

- Carbon Emission Intensity Calculation/Limitation

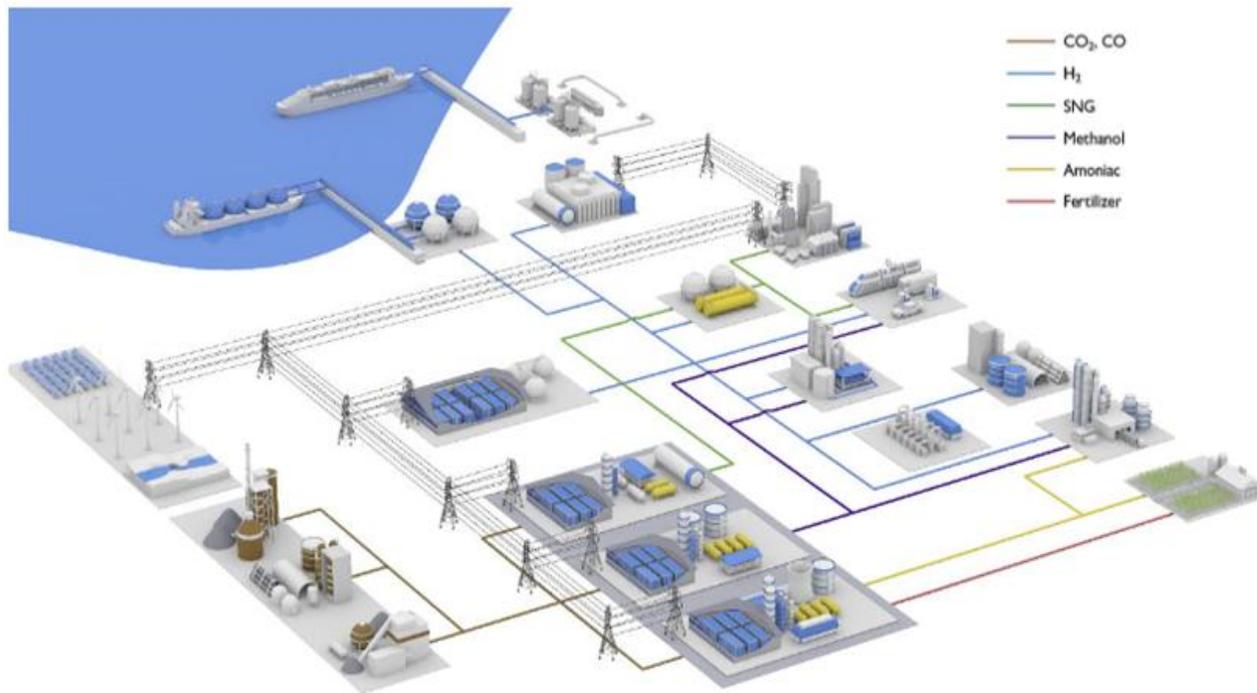
$$i_{e,H_2} = \frac{E_{Grid} \times i_{e,Grid}}{d_{H_2}}$$

- ❑ **IMO MEPC 80:** Cut annual greenhouse gas (GHG) emissions from international shipping by at least 20%, with an ambition to reach **30%, by 2030** compared to 2008.
- ❑ **USA:** Clean Shipping Act
- ❑ **EU:** EU Emission Trading System (ETS) ^[1]、FuelEU Maritime Regulation^[2]

- **EU ETS^[1]:** All ships above 5000 GT entering or leaving European Economic Area (EEA) ports are required to **purchase EU Allowances (EUAs)** to cover emissions while navigating and berthing within the EEA.
- **FuelEU Maritime Regulation^[2]:** Set targets to reduce the GHG emission intensity of ships. Compared to a 2020 baseline, the required emission intensity should be reduced by **2% in 2025** and **80% by 2050**.



- ❑ In the first half of 2024, **alternative fuel-powered ships accounted for 41%** of the new ship orders globally
- ❑ Main alternative, the **renewable fuels of non-biological origin (RFNBO)**, are **green hydrogen**
- ❑ With carbon policies, shipping companies are willing to pay for the transition to RFNBO



**Power-to-X schematic diagram
for RFNBO production**

- **Green Methanol**—The most economical RFNBO^[1].
- Using power from offshore wind farm (OWF) for methanol production and supplying to the shipping industry has great potential:
 - ✓ In-situ production and refueling
 - ✓ EU OWFs exhibit higher utilization hours and lower costs compared to most renewable energy sources^[2]
 - ✓ Green methanol production can leverage existing infrastructure through out-of-the-box solutions

[1] Stolz, B., Held, M., Georges, G. et al. Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. *Nat. Energy* 7, 203–212 (2022).

[2] Brandt, J., Iversen, T., Eckert, C., et al. Cost and competitiveness of green hydrogen and the effects of the European Union regulatory framework. *Nat. Energy* 9, 703–713 (2024).



Report Outline

01 Background

02 Methodology

03 Results Analysis

04 Related Research

System Configur.

- Design in-situ production and refueling of green methanol system with multi-energy coupling
- Electricity and carbon capture sources that meet the EU Renewable Energy Directive (RED)

Scenarios & Indicator Design

- Generate system configuration scenarios with different electricity and carbon sources
- Introduce evaluation indicators to assist scenario decision-making

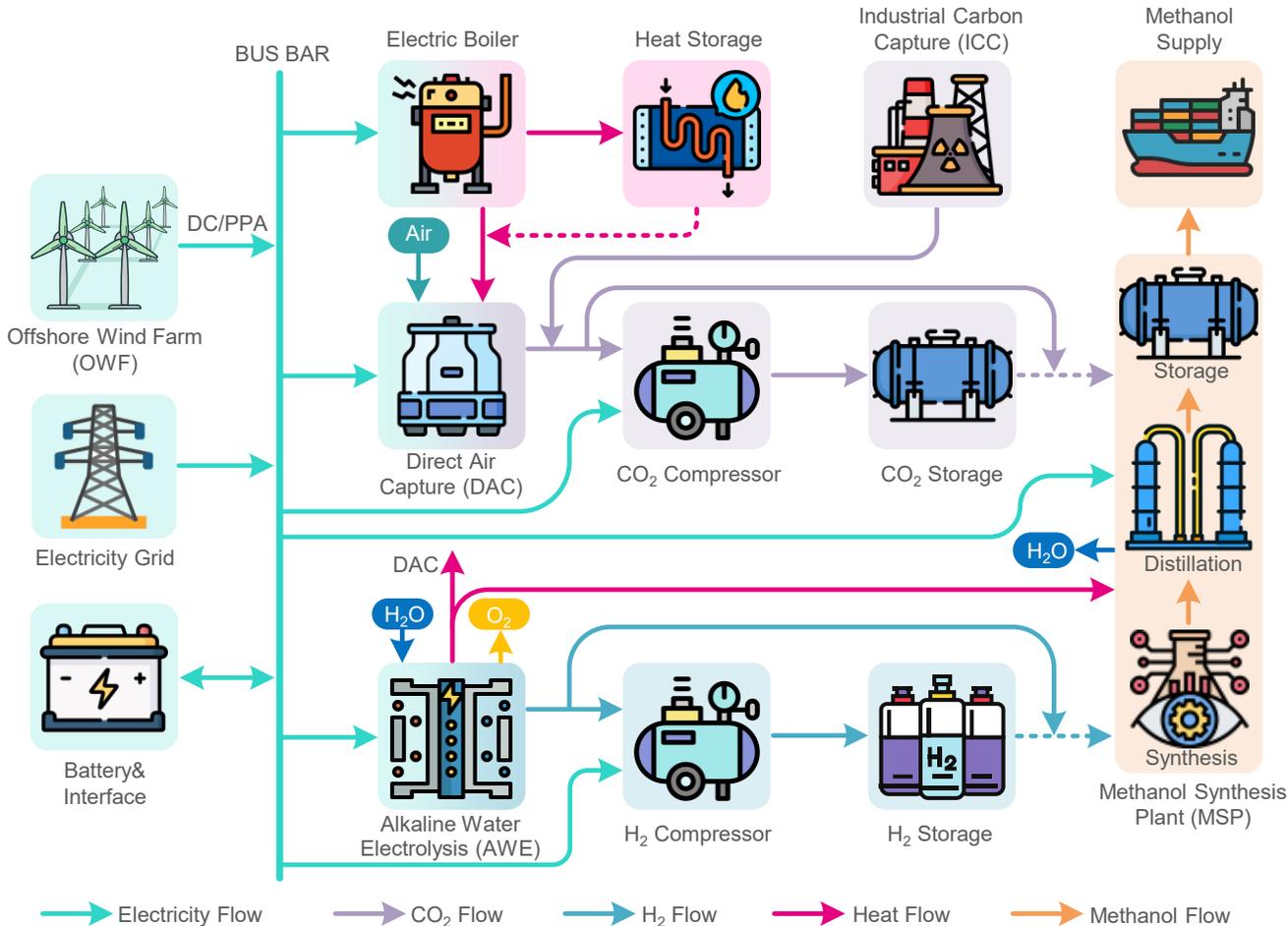
Optimal Planning

- Objective function: Minimize the levelized cost of methanol (LCOM)
- Decision variables: Rated capacity of devices + 8760-hour operation variables

System Configuration



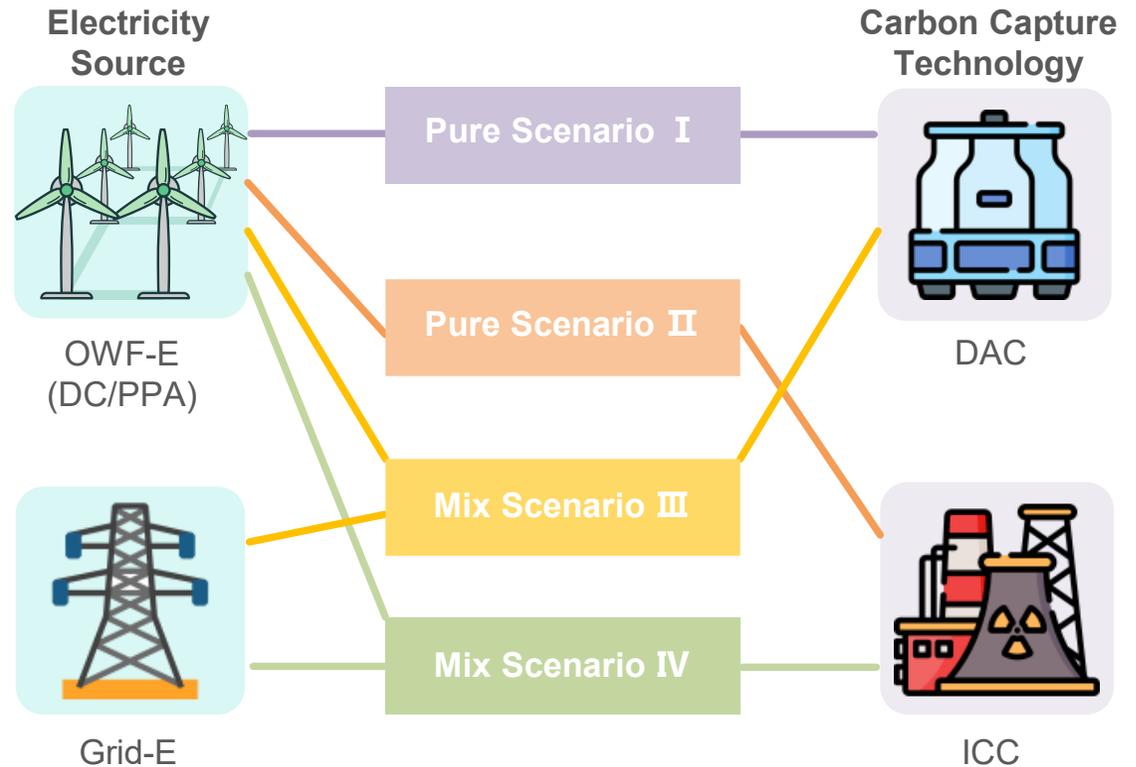
- ❑ Electricity, heat, gas (hydrogen, methanol), carbon multi-energy coupling
- ❑ Meet the EU RED^[1-3] required electricity and carbon sources



- ✓ **Electricity:** OWF, electricity grid, battery energy storage
- ✓ **Gas:** Methanol synthesis system (MSP), alkaline water electrolysis (AWE), hydrogen compressor and storage
- ✓ **Heat:** Waste heat from electrolysis, electric boilers, heat storage
- ✓ **Carbon:** Direct air capture (DAC), Industrial carbon capture (ICC), carbon compressor and storage

□ Combining different electricity sources and carbon capture technologies yields 4 scenarios

- ◆ Electricity of OWF (OWF-E) is necessary.
- ◆ Whether to use the electricity from grid (Grid-E) divide the scenario into **Pure Scenario** and **Mix Scenario**.
- ◆ Technical combinations of 4 scenarios:
 - ✓ Pure Scenario I: OWF-E + DAC
 - ✓ Pure Scenario II: OWF-E + ICC
 - ✓ Mix Scenario III: (OWF-E+Grid-E) + DAC
 - ✓ Mix Scenario IV: (OWF-E+Grid-E) + ICC



□ Evaluation indicators

- Economic indicators LCOM; “Green” indicators **GHG emissions savings (GHG-ES)**
- Other indicators: Grid-E annual total volume, annual methanol production...

Input and output characteristic of devices

Energy balance $EF_{h,k}^{\text{EX}} + \sum_{n=1}^N EF_{n,h,k}^{\text{OUT}} = \sum_{n=1}^N EF_{n,h,k}^{\text{IN}}, \forall h, k$

Energy conversion $EF_{n,h,k}^{\text{OUT}} = \lambda_{n,k',k} \times EF_{n,h,k'}^{\text{IN}}, \forall n, h, k, k'$

Working scope $CAP_{n,k} \geq 0, \forall n, k$
 $\xi_{n,k}^{\text{MIN}} CAP_{n,k} \leq EF_{n,h,k}^{\text{IN}} \leq \xi_{n,k}^{\text{MAX}} CAP_{n,k}, \forall n, k$

Ramping constraint $EF_{n,h,k}^{\text{IN}} - EF_{n,h-1,k}^{\text{IN}} \leq \mu_{n,k}^{\text{UP}} \times EF_{n,h-1,k}^{\text{IN}}, \forall n, h, k$
 $EF_{n,h-1,k}^{\text{IN}} - EF_{n,h,k}^{\text{IN}} \leq \mu_{n,k}^{\text{DOWN}} \times EF_{n,h-1,k}^{\text{IN}}, \forall n, h, k$

Models of various energy storage devices

$$\delta_{n,h,k}^{\text{IN}} + \delta_{n,h,k}^{\text{OUT}} = 1, \delta_{n,h,k}^{\text{IN}}, \delta_{n,h,k}^{\text{OUT}} \in \{0,1\}$$

$$0 \leq EF_{n,h,k}^{\text{IN}} \leq \delta_{n,h,k}^{\text{IN}} \times \xi_{n,k}^{\text{MAX}} \times CAP_{n,k}$$

$$0 \leq EF_{n,h,k}^{\text{OUT}} \leq \delta_{n,h,k}^{\text{OUT}} \times \xi_{n,k}^{\text{MAX}} \times CAP_{n,k}$$

$$SOC_{n,k}^{\text{MIN}} \leq SOC_{n,h,k} \leq SOC_{n,k}^{\text{MAX}}$$

$$SOC_{n,h,k} = SOC_{n,h-1,k} + \left(\eta_{n,k}^{\text{IN}} \times EF_{n,h,k}^{\text{IN}} - \frac{EF_{n,h,k}^{\text{OUT}}}{\eta_{n,k}^{\text{OUT}}} \right) \times \Delta h$$



Objective function: Minimize LCOM

$$\min LCOM = \frac{\sum_{n=1}^N (CAPEX_n + OPEX_n) + EC}{\text{Methanol Production}}$$

CAPEX: Capital Expenditure

OPEX: O&M Expenses

EC: External costs



Report Outline

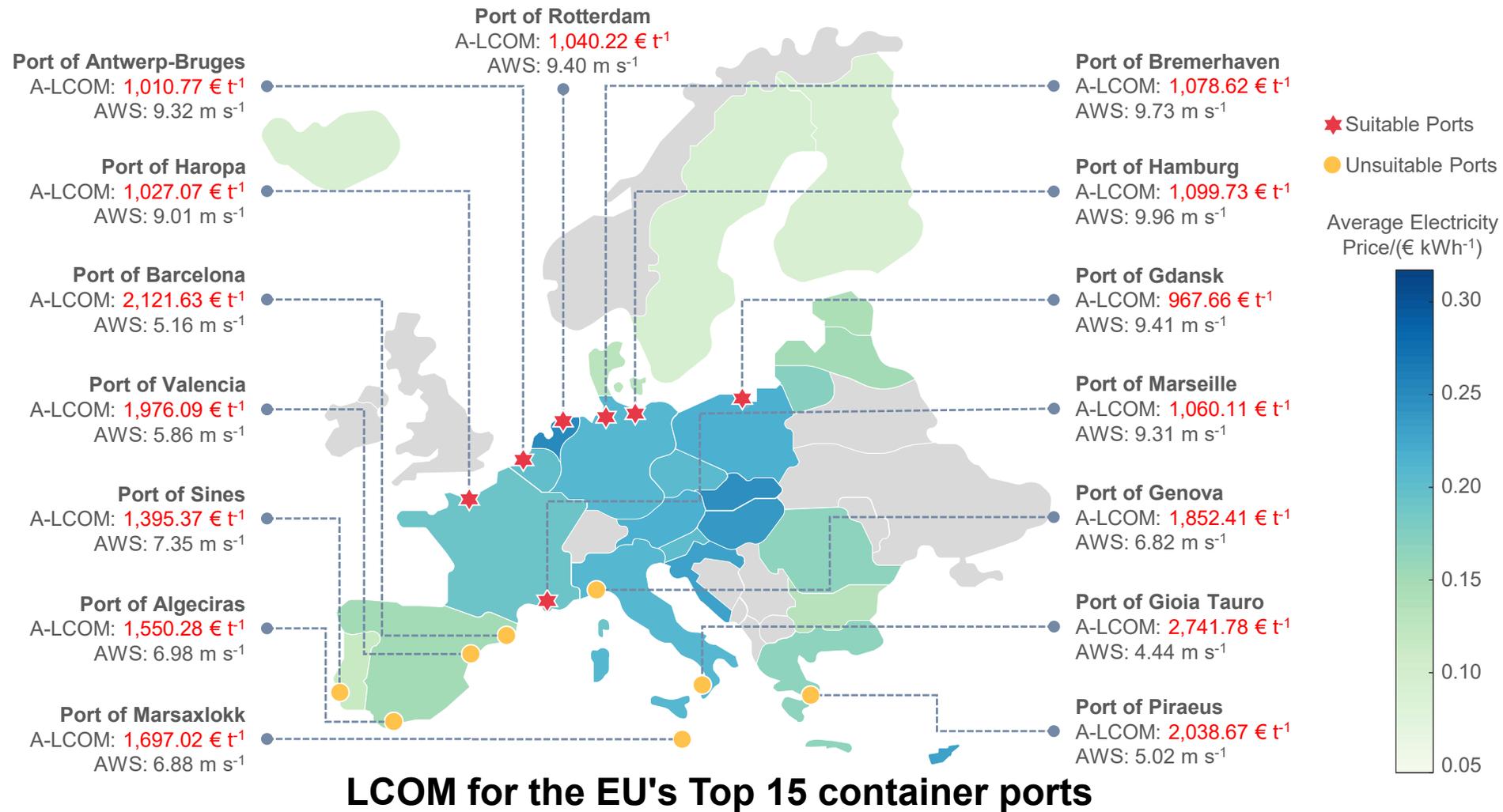
01 Background

02 Methodology

03 Results Analysis

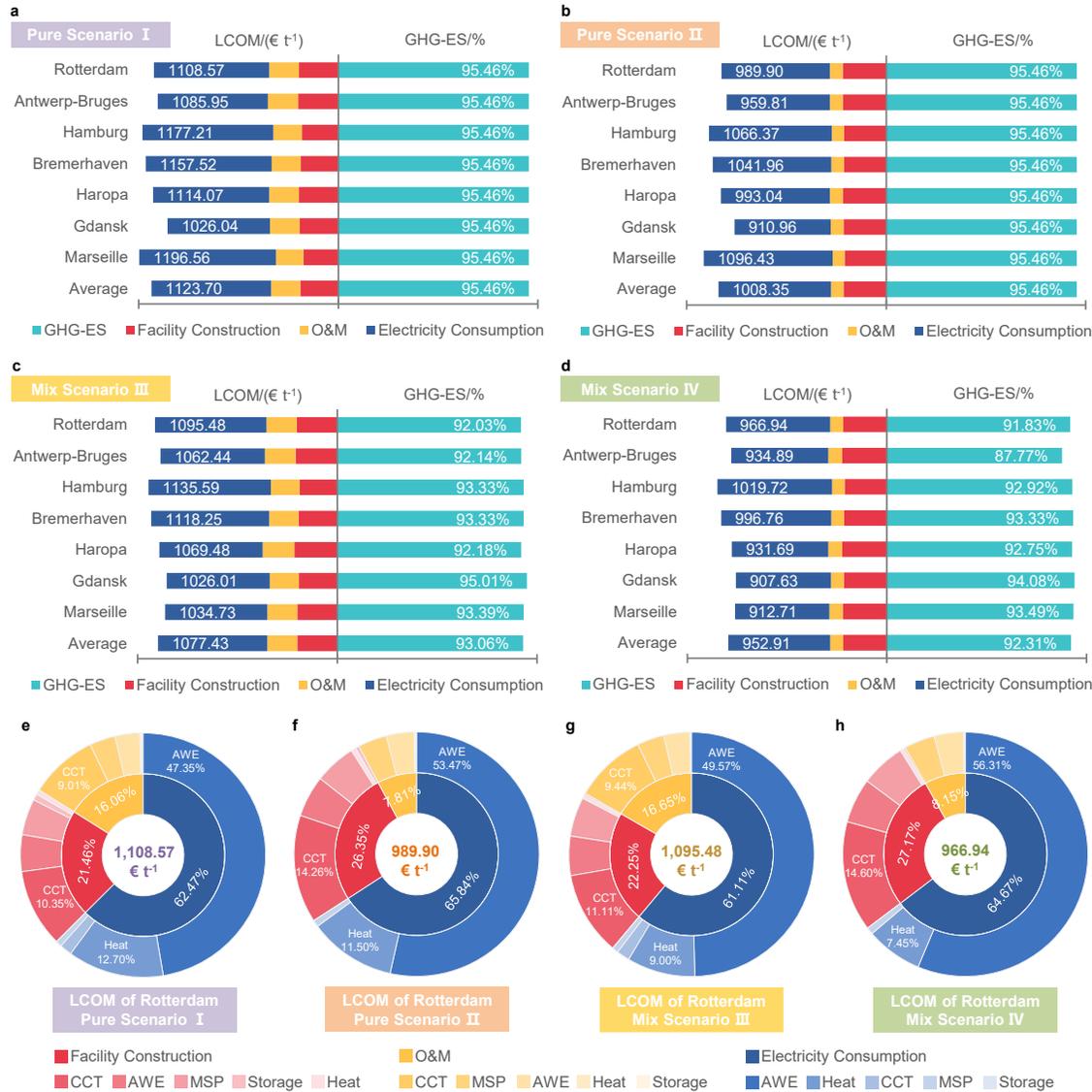
04 Related Research

Production potential of green methanol in EU ports



Not all ports are suitable for producing green methanol (★ are)

Production potential of green methanol in EU ports

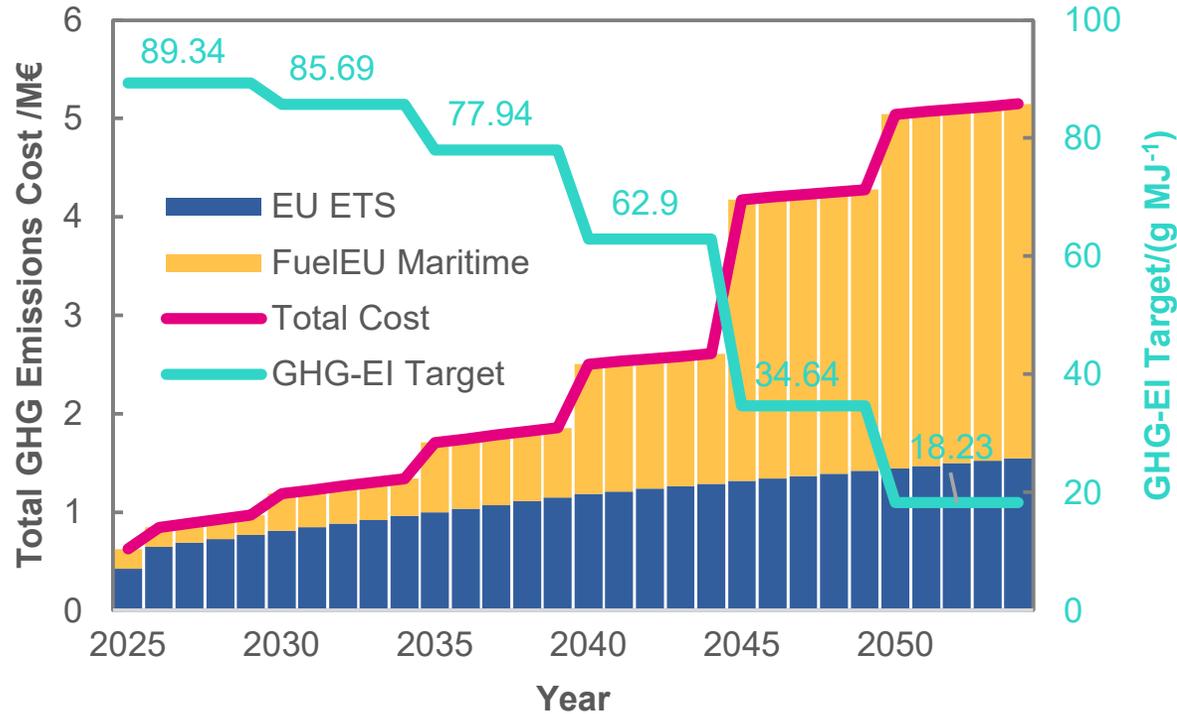


In 2025:

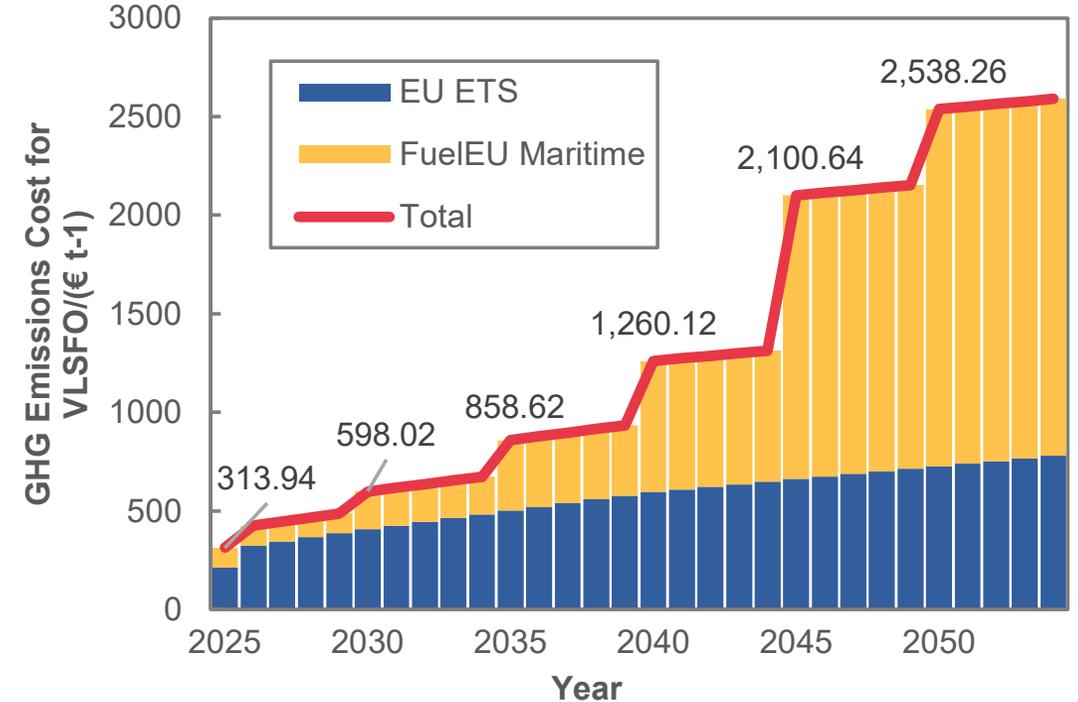
- LCOM is 907.63-1196.56 €/t, and electricity consumption accounts for >60%.
- The limited power supply of grid can smooth wind power thus reducing LCOM (III < I, IV < II)
- Carbon source: ICC is more economical than DAC (II < I, IV < III)

LCOM and GHG-ES for green methanol in selected 7 ports

Conventional marine fuel cost forecast



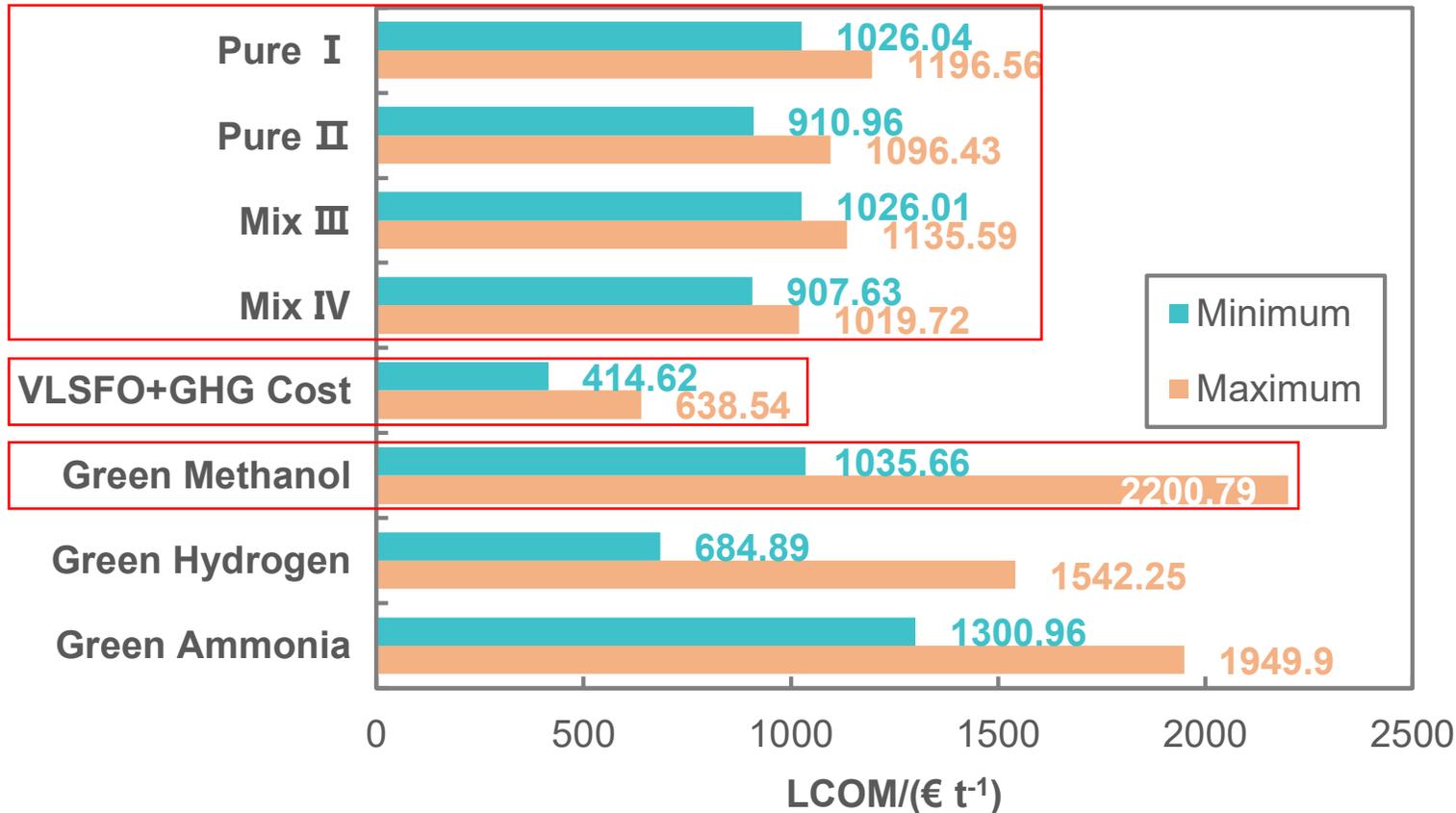
2025~2050 GHG costs for a large ship sailing within EEA



2025~2050 GHG emissions cost with conventional fuels very low sulfur fuel oil (VLSFO)

- ❑ GHG emissions costs increase dramatically in the next few years with carbon policies.
- ❑ From 2025 to 2040, the cost imposed by FuelEU Maritime is lower than that of the EU ETS; however, it escalates notably post-2040.
- ❑ Overall, there is a sufficient buffer period (2025-2040) for the transition to green maritime transport.

Comparison between green methanol and VLSFO



The equivalent LCOM of several potential solutions in 2025

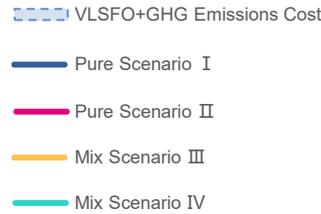
- LCOM of different scenarios is much lower than that of most current green methanol projects (1035.66~2200.79€/t).
- The emission costs imposed on VLSFO are lower, with **equivalent LCOM of 414.62~638.54 €/t**.
- This may incentivize container ship operators to comply with regulations by paying fines rather than transitioning to green fuels.

Comparison between green methanol and VLSFO

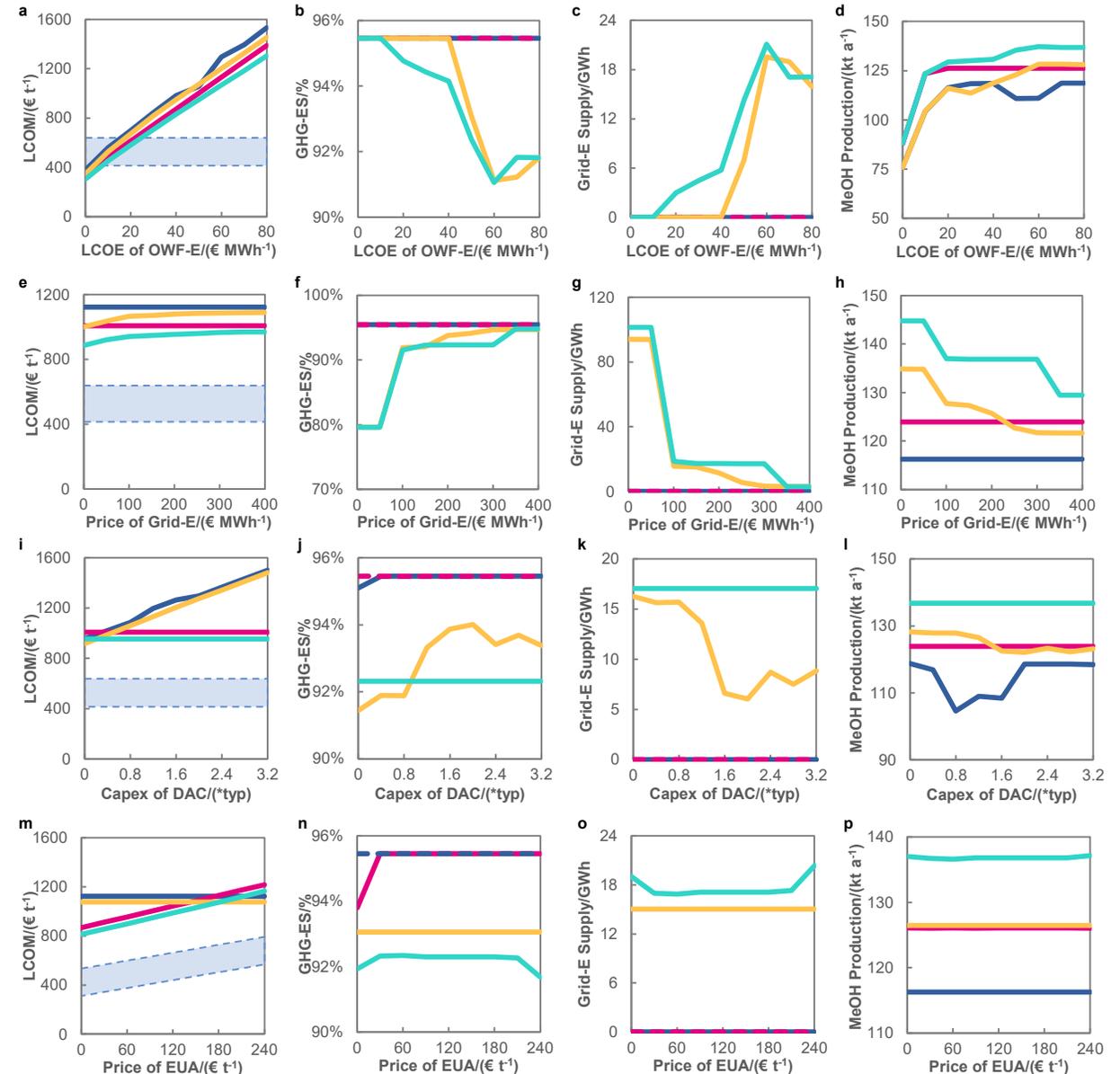


□ Sensitivity analysis of key factors

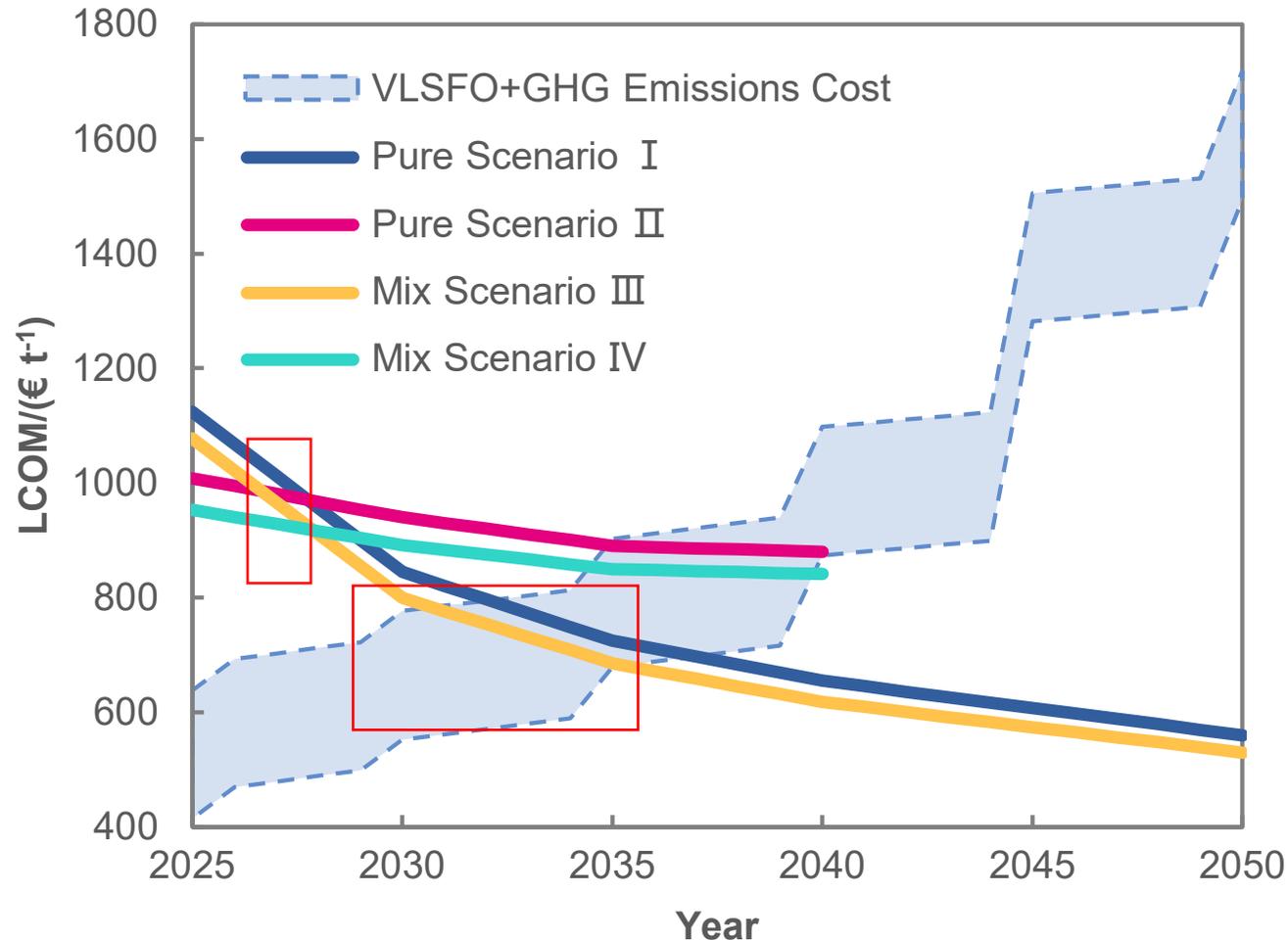
- wind power price
- electricity price
- DAC cost
- carbon price
- ...



□ Within the variable range, currently green methanol still lacks cost competitiveness compared with VLSFO!



Forecast of future cost competitiveness



**2025~2050 LCOM changes in different scenarios
(ICC is only allowed to be used until 2041)**

- ❑ LCOM will **decrease by 50% in 2025~2050**
- ❑ **Competitiveness: Green methanol will reach cost parity with VLSFO in 2030-2035**, driven by two mechanisms:
 - ✓ **EU ETS and Fuel EU Maritime** are expected to increase VLSFO costs by 85.7%-158.9% by 2035
 - ✓ **Technological progress** reduces green methanol LCOM by 10.8%-36.4%
- ❑ **Carbon source:** With the rise of carbon prices and the maturity of DAC, **DAC can replace ICC as a more economical carbon source before 2030** (I < II , III < IV)

Research Significance

- As carbon policies continue to strengthen, shipping industry is looking for green fuels
- The economic benefits of **green hydrogen** are gradually emerging due to green premium

Research Methods

- Model design: Optimal planning of in-situ production and refueling of **green methanol** system
- Economic evaluation: Considering the impact of the issued EU ETS and FuelEU regulations, the cost competitiveness of produced green methanol is evaluated.

Main Conclusions

- **By 2030-2035, the cost of producing green methanol from OWF will be lower than that of VLSFO.**



Report Outline

01 Background

02 Methodology

03 Results Analysis

04 Related Research

Key Challenges: Optimize the cost/benefit of offshore wind farm (OWF) & Energy Islands:



Wake effect among WTGs

Layout to **reduce wake and increase power generation**

Wake effect
Strong non-convex



Long MTTR (**reliability**)

Balancing economy and reliability

Objective/constraint
complex



More products (**economy**)

Reduce levelized cost of hydrogen (**LCOH**)

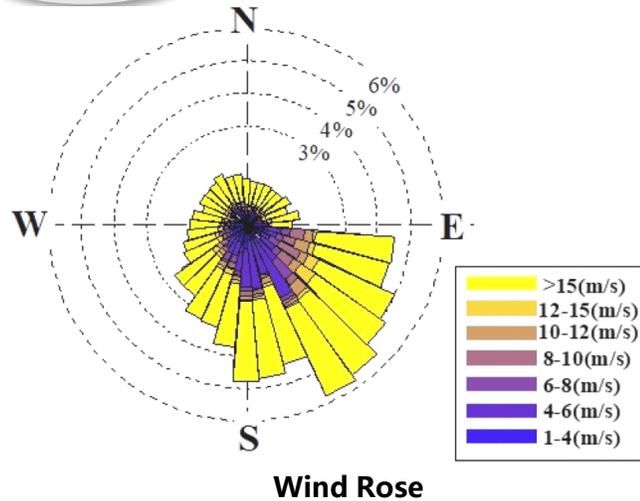
Dynamic electrolysis characteristics

$$\begin{aligned} \min F(x) \\ \text{s. t. } G(x) \leq 0 \\ x \in D \end{aligned}$$

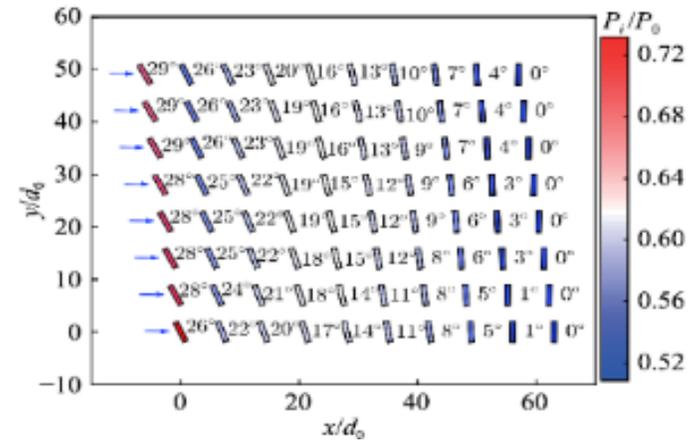
Key Scientific Issues: Modeling and solving
Complex Combinatorial Optimization problems

Key issue

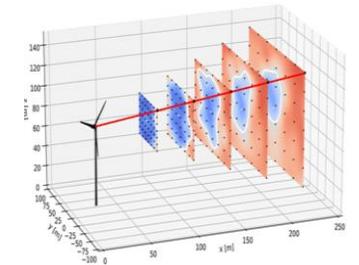
Reducing wake effect by placing WTs in proper positions



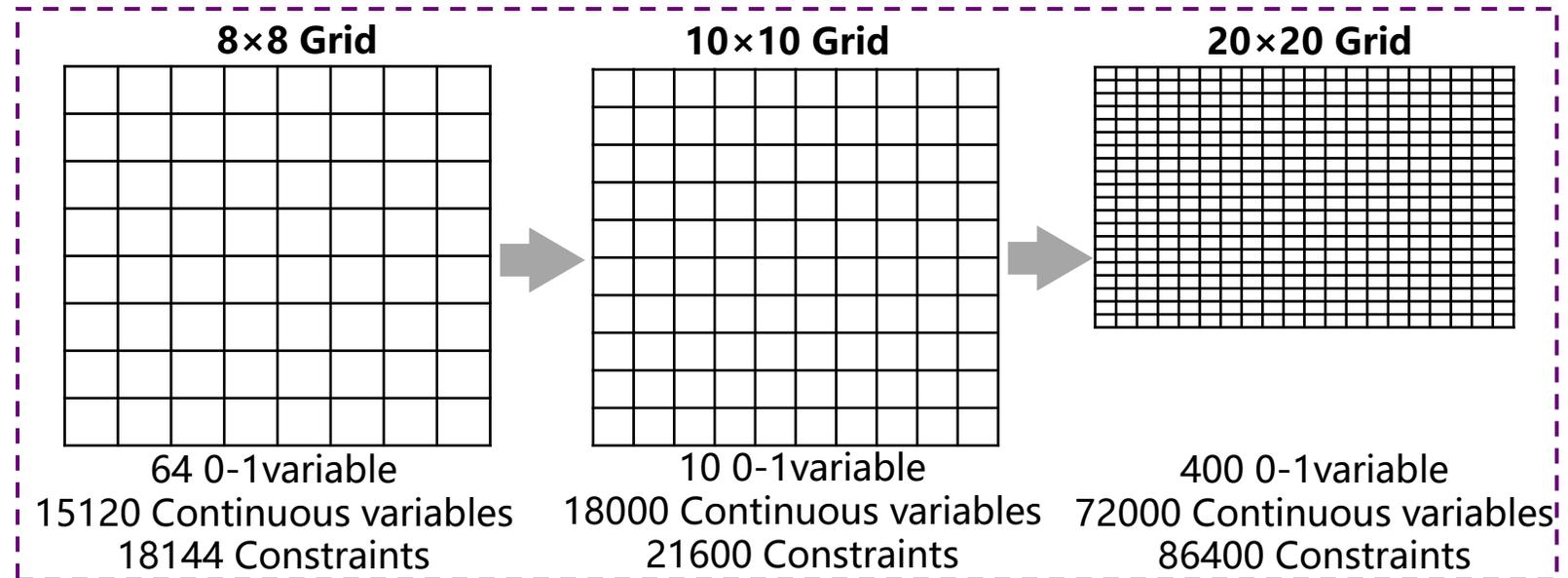
Depicting multi wind scenes based on wind rose diagram



Wake quantification index



Facing the disaster of dimensionality as the scale increases

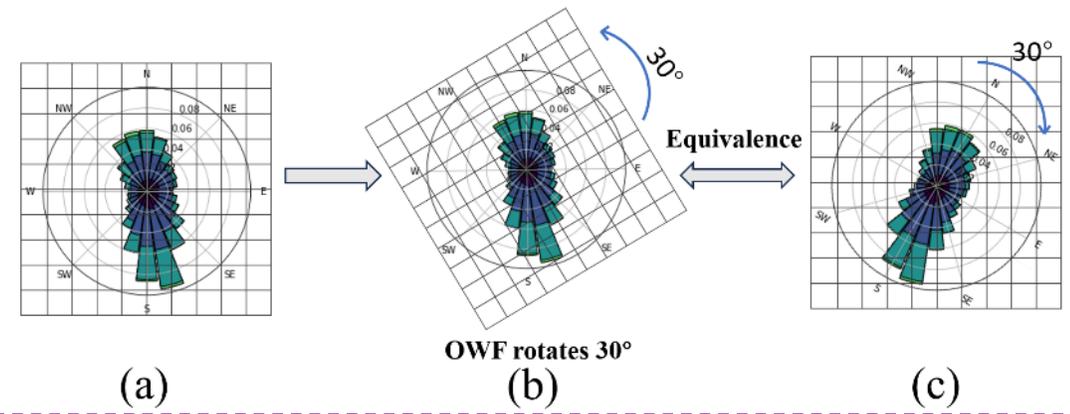


Ideas

Meshing WT layout, introducing rotating coordinates;
Combining **Mathematical Optimization** with meta-heuristic algorithms

Rotate coordinates for scene decoupling

- Rotate the horizontal grid by different angles to obtain WT layout schemes at different angles from the horizontal axis, improving the diversity of WT layouts



Large-scale MIP-based model for initial solution

$$\min \sum_{i \in \mathcal{N}} \sum_{d \in \mathcal{D}} \left(\frac{1}{3} u_{id, \infty}^3 x_i - \sum_{j \in \mathcal{N}} \frac{1}{3} (u_{id, \infty}^3 - u_{jd, \infty}^3) y_{ij} \right) P_d$$

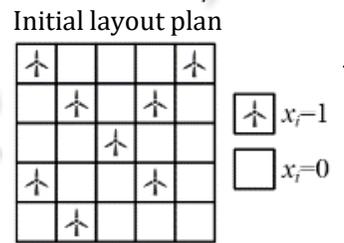
$$st \quad \sum_{i \in \mathcal{N}} x_i = m$$

$$x_i + x_j \leq 1 \quad \forall (i, j) \in \mathcal{E}$$

$$x_i + x_j - 1 \leq y_{ij} \quad \forall i, j \in \mathcal{N}$$

$$y_{ij} \geq 0 \quad \forall i, j \in \mathcal{N}$$

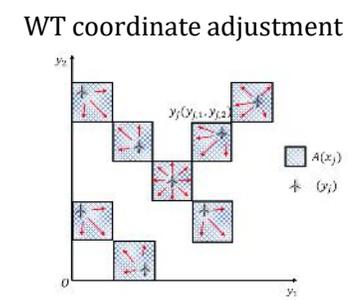
$$x_i \in \{0, 1\} \quad \forall i \in \mathcal{N}$$



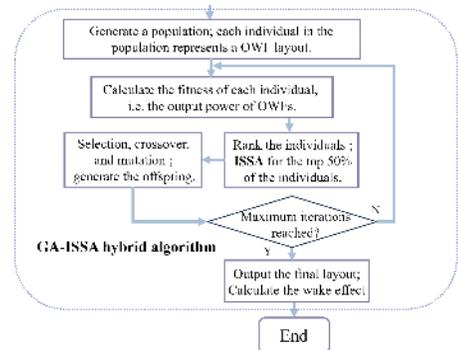
High-quality initial feasible solution \rightarrow

Establishing a large-scale integer programming problem based on parameterized wake model and discrete point selection

Heuristic algorithm to further optimize WT coordinates in grid



WT coordinates are used as decision variables and heuristic algorithms are used for layout optimization



➤ Two-stage optimization model for micro-siting

1. Solve grid-based model by mathematical programming

$$\max \sum_{n \in N} \sum_{j \in I} \pi^n P_j^n (x_j, v_{ij,j}^n) \quad \text{Total power generation}$$

Decision variables

$$\text{s.t. } \sum_{j \in I} x_j = M \quad \text{Total number of WTs}$$

$$P_j^n \leq P_{rate,j} x_j \quad \forall i \in I$$

WT output constraints

$$P_j^n \leq P(v_j^n) \quad \forall i \in I$$

$$v_j^n = v_{max,j}^n - \sqrt{\sum_{i \in I \setminus j} x_i (v_{max,j}^n - v_{ij,j}^n)^2} \quad \forall j \in I$$

Sum of squared wakes from multiple WTs

$$v_{ij,j}^n = v_{max,j}^n (1 - w_{ij}^n x_j)$$

$$x_j + x_i \leq 1 \quad \forall j, i \in I: \text{distance}(j, i) < D_{min}$$

Minimum safety distance constraint

$x_i, x_j \in \{0, 1\}$

2. Further optimization of WT coordinates

$$\max \sum_{n \in N} \sum_{j \in M} \pi^n P_j^n (y, v_j^n)$$

Decision variables: $y = (y_{j,1}, y_{j,2})$

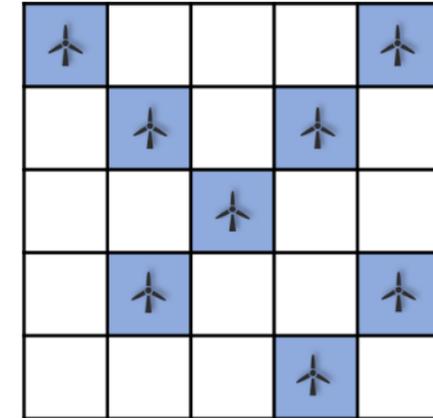
$$\text{s.t. } (y_{i,1}, y_{i,2}) \in A(x_i)$$

$$(y_{i,1} - y_{j,1})^2 + (y_{i,2} - y_{j,2})^2 \leq D_{min}^2 \quad \forall i, j \in M$$

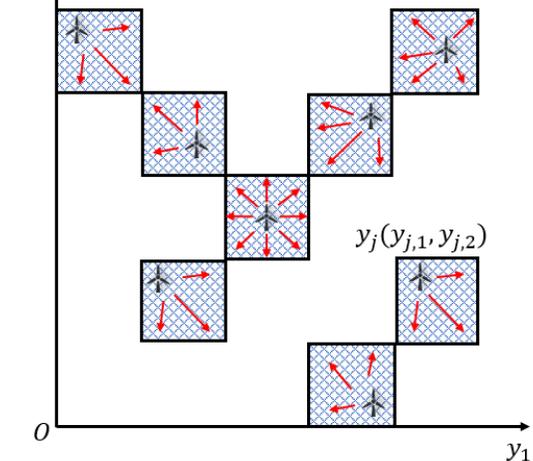
Minimum safety distance constraint

• Schematic diagram

Stage 1: $x_j = 1$ $x_j = 0$

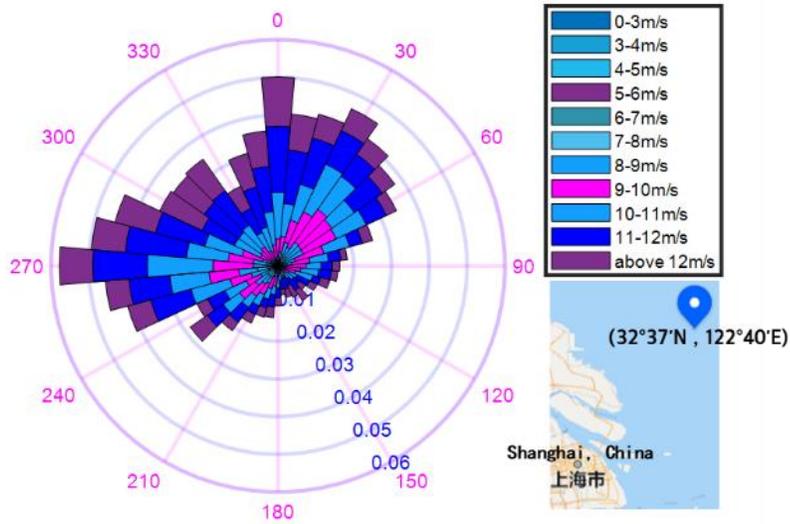


Stage 2: $A(x_j)$ $\uparrow(y_j)$



➤ Two-stage optimization model for micro-siting

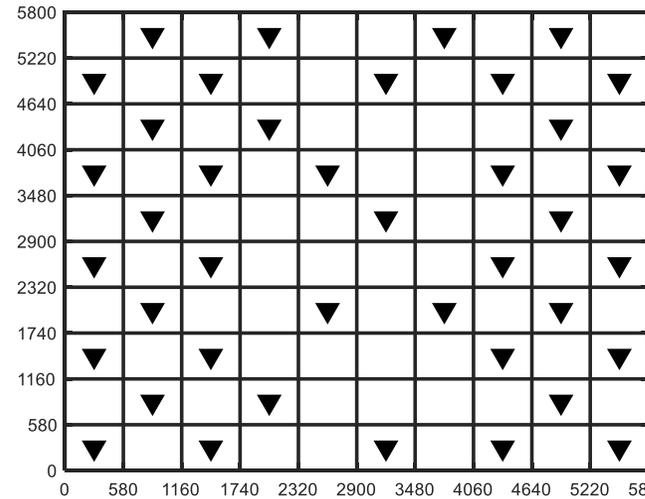
• Case studies



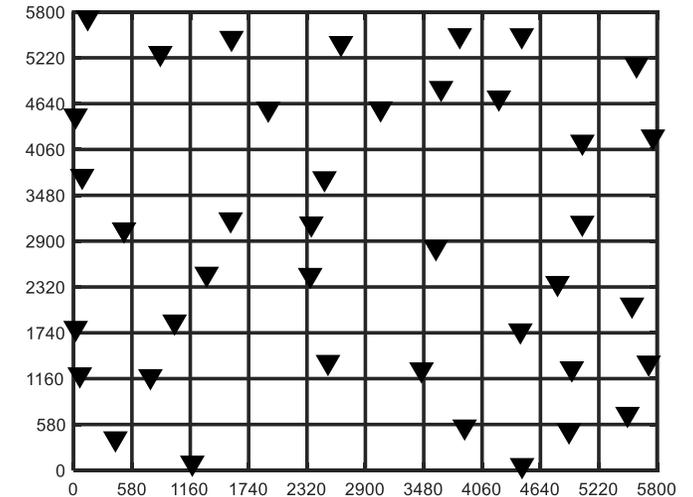
Jiangsu 200MW OWF micro-siting

• Results comparison of manual and proposed method

Typical layout for manual scheme



Results of the two-stage optimization



Results comparison

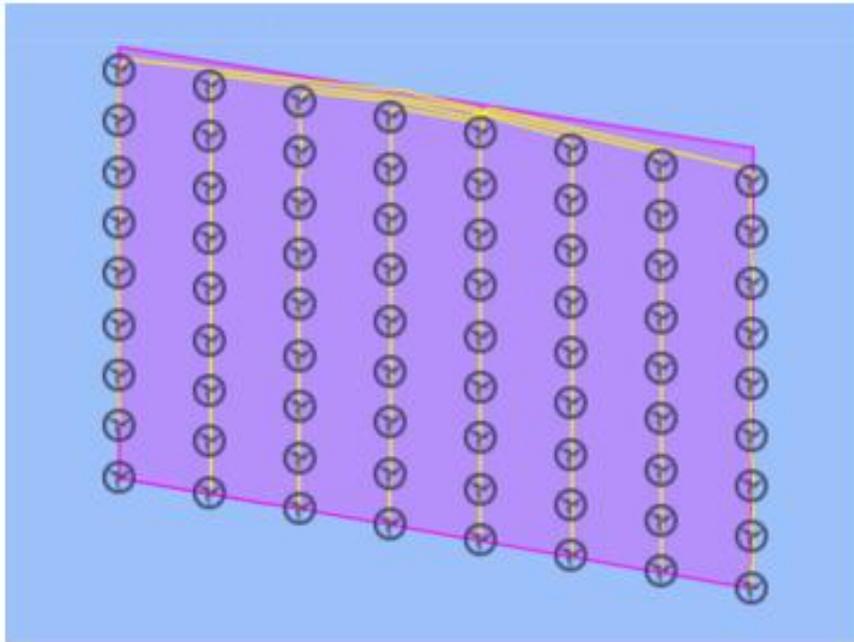
Scheme	Wake Model	Power generation (MW)	Wake loss(%)
Manual	Gauss-Jensen	116.5	17.7
Proposed method	Gauss-Jensen	126.6	20.2

After layout optimization:

- Average power generation increases **8.7%**
- Annual power generation increases **8.8×10^7 kWh**
- Annual revenue increases **35 million CNY** (assume 0.4 CNY/kWh of offshore wind power)

Key issue

OWFs need regular layout, considering requirement from industry.



OWFs in Europe(Left)and China Yangjiang (right)

Regular layout of OWF

Necessity:

- 1) reducing the visual impact of nearshore OWF and enhancing the aesthetic appeal of OWFs;
- 2) lowering the construction costs of infrastructure;
- 3) facilitating O&M activities;
- 4) benefiting search and rescue operations

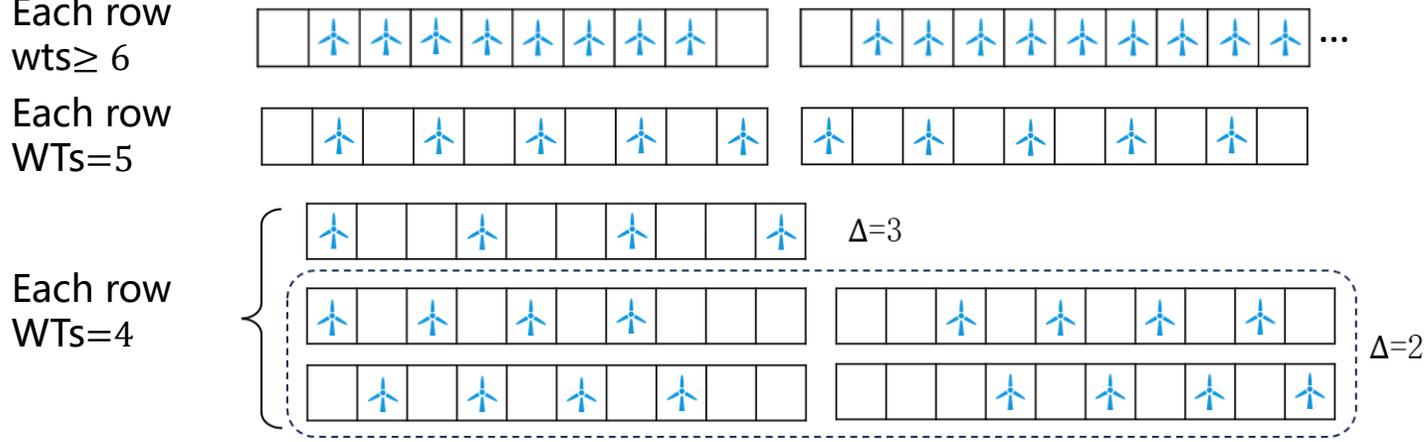
Constraints:

- 1) Number of WTs per row for 0 or n;
- 2) The distance between adjacent WTs is the same



➤ Micro-siting model for WTs considering regular layout

- Number of WTs in each row and the spacing between WTs



- Phase 1 MILP Model** $\max \sum_{n \in N} \sum_{i \in I} \pi^n \hat{P}_i^n(x_i, v_i^n)$ **Power curve piecewise linearization**

$$\begin{aligned}
 & s.t. \sum_{i \in I} x_i = N \\
 & x_j + x_i \leq 1 \quad \forall j, i \in I: d(j, i) < D_{min} \\
 & v_j^n = v_0^n \left(1 - \sum_{i \in I/j} x_i w_{ij}^n \right) \quad \forall i, j \in I \\
 & \hat{P}_i^n \leq P_{rate} x_i \quad \forall i \in I \\
 & \sum_{l \in L} \eta_{i,l}^n = 1 \quad \forall i \in I \quad \forall l \in L \\
 & \sum_{l \in L} \eta_{i,l}^n v_{s,l} \leq v_i^n \leq \sum_{l \in L} \eta_{i,l}^n v_{h,l} \quad \forall i \in I \\
 & \hat{P}_i^n \leq P \left(\sum_{l \in L} \eta_{i,l}^n v_{m,l} \right) \quad \forall i \in I \\
 & \text{Regular layout constraints} \quad x_i \leq \sum_{j \in \bar{I}_i} x_j \quad \forall i, j \in I
 \end{aligned}$$

- Phase 2 Continuous model**

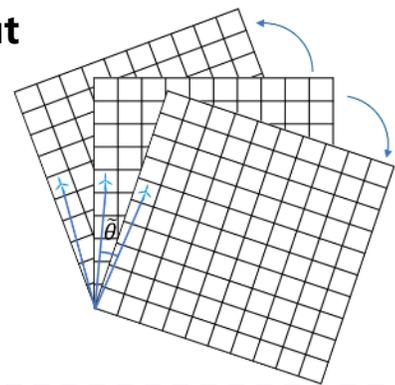
$$\max \sum_{n \in N} \sum_{i \in I} \pi^n P_i^n(x, v_i^n)$$

$$\begin{aligned}
 & s.t. (x_{i,1}, x_{i,2}) \in A(x_i) \quad \forall i \in I \\
 & (x_{i,1}^1, x_{i,2}^1) \in A(x_i) \quad \forall i \in \bar{I}
 \end{aligned}$$

$$\begin{aligned}
 & (x_{i,1} - x_{j,1})^2 + (x_{i,2} - x_{j,2})^2 \leq D_{min}^2 \quad \forall i, j \in I \\
 \text{Rotation Constraint} & \begin{cases} x_{i,1} = x_{i,1} \cos \theta - x_{i,2} \sin \theta \\ x_{i,2} = x_{i,1} \sin \theta + x_{i,2} \cos \theta \end{cases} \quad \forall i \in I
 \end{aligned}$$

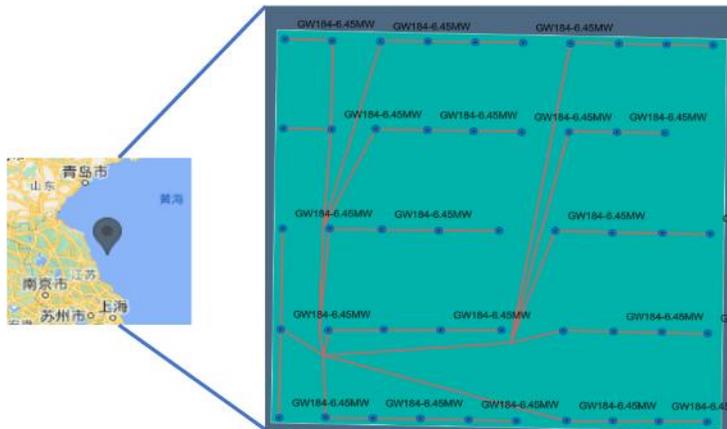
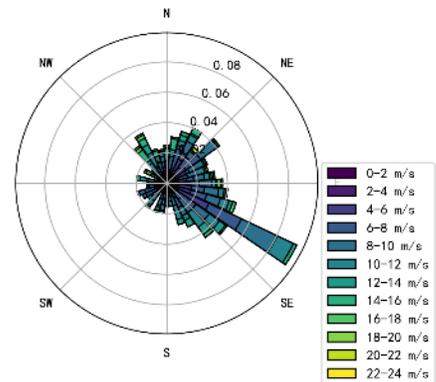
$$\begin{aligned}
 & v_j^n = v_0^n \left(1 - \sqrt{\sum_{i \in I/j} x_i (w_{ij}^n)^2} \right) \quad \forall i, j \in I \\
 & \begin{cases} x_{j,1}^k = x_{i,1}^1 + (k-1)\chi \\ x_{j,2}^k = x_{i,2}^1 \end{cases} \quad \forall i, j \in \bar{I} \quad \forall k \in [1, y]
 \end{aligned}$$

Regular layout constraints



➤ Micro-siting model for WTs considering regular layout

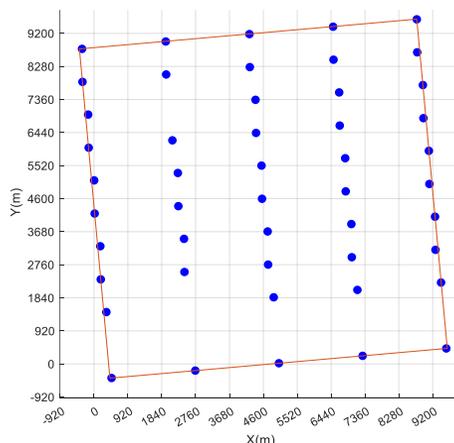
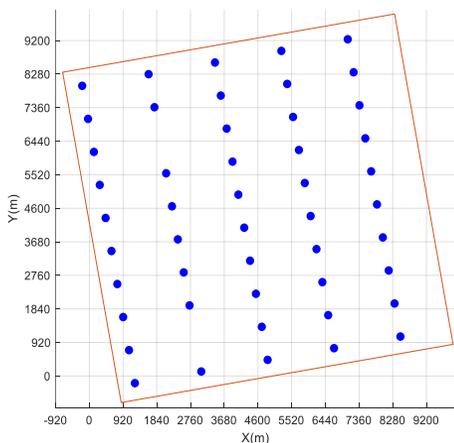
• Actual Cases



Actual wind rose

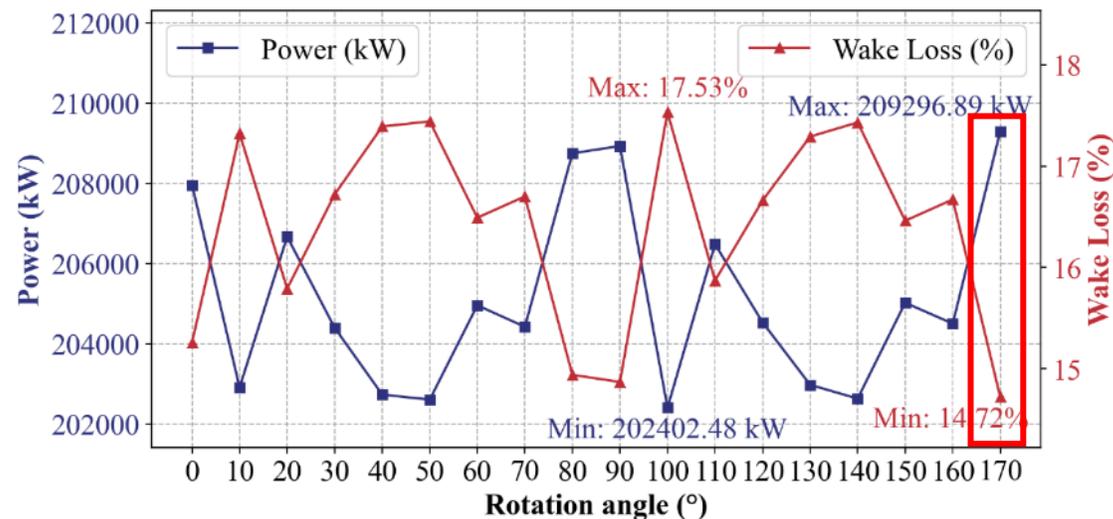
Jiangsu Dafeng H4 OWF

• Optimization results



Phase 1 layout (left) and phase 2 layout (right)

• Phase 1 result



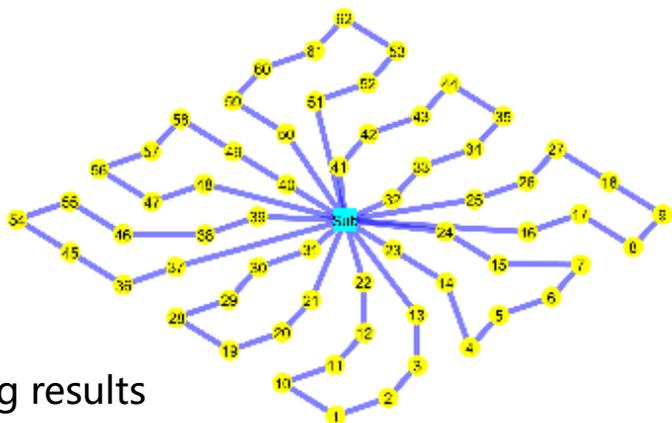
• Phase 2 result comparison

Scheme	Wake Model	Power generation (kW)	Wake loss(%)
Existing approach	Cosine	207142.2	15.60
Proposed approach	Cosine	216385.7	11.83

Key Issue

How to balance **economy** and **reliability** for optimizing large-scale OWF Electrical Collector System (ECS)?

Improved CVRP-based ECS planning

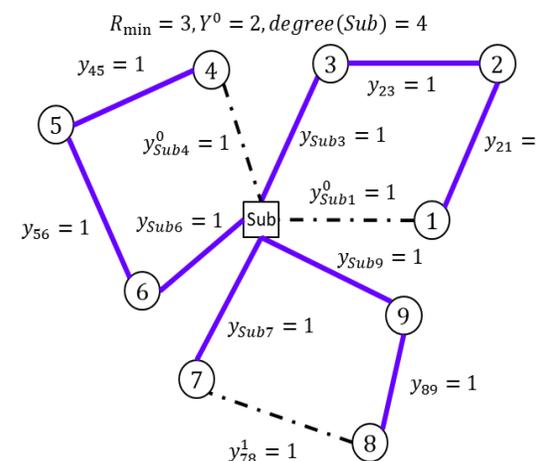


ECS planning results

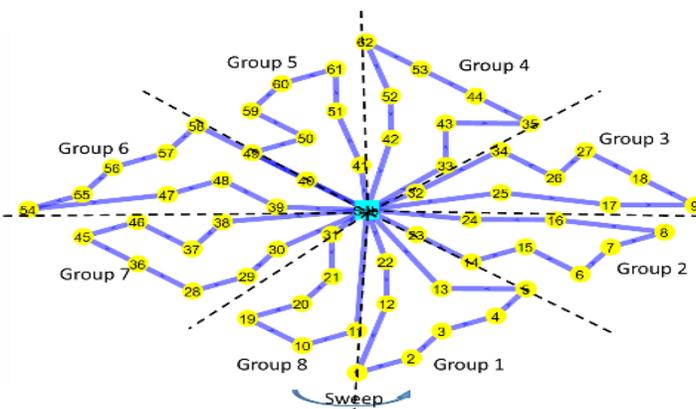
$$\min_{x,P} \sum_{(i,j) \in L} c_{ij} x_{ij} + \eta \sum_{(i,j) \in L} r_{ij} P_{ij}^2$$

- s. t.
- CVRP model
 - Cable crossing avoid constraints
 - Power grid planning model
 - k-degree centrality tree model

Accelerated solving algorithm of ECS planning



Projection cut set model nether improvements



Initial feasible solution search

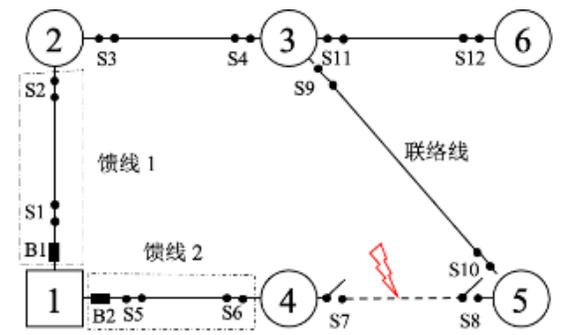
Key Issue

How to balance **economy** and **reliability** for optimizing large-scale OWF Electrical Collector System (ECS)?

ECS planning with reliability constraints

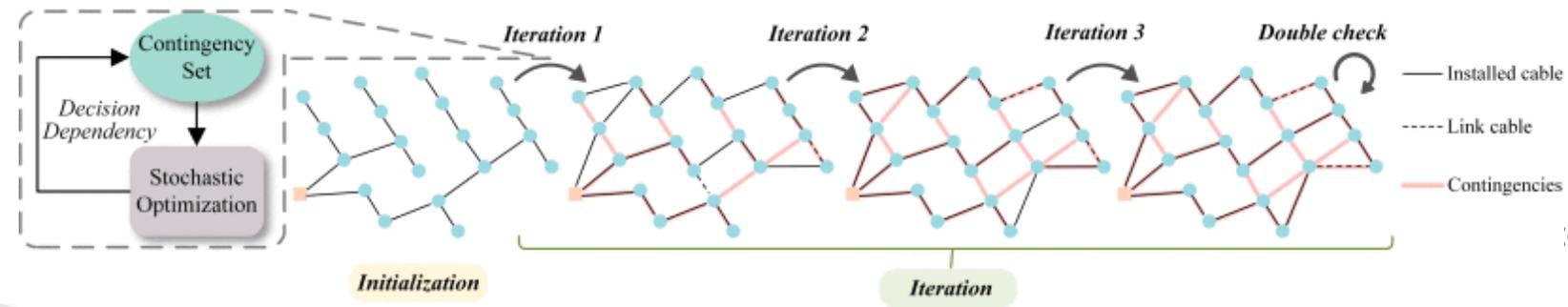
$$\min C_{cap} \sum_{ij \in \Psi_B} d_{ij} l_{ij} + \omega EEND$$

- s. t. Operational constraints
 Network reconfiguration model
 Reliability assessment model
 Reliability requirement constraints



Post-failure network reconstruction modeling

Accelerated solving algorithm of ECS planning



Customized Progressive Contingency Incorporation (CPCI) "decomposition-coordination" parallel computing

Ideas

Consider cable selection, switch configuration, post-fault reconfiguration, etc. to formulate and solve **MIP** models of ECS planning.

- ❑ **Key challenges:** How to consider complex constraints, economic and reliability to optimize ECS?
- ❑ **For ring topology,** a Capacitated Vehicle Routing Problem (CVRP) model is proposed, with Multiple Traveling Salesman Problem (mTSP) to tighten the lower bound and speeds solution.

CVRP model

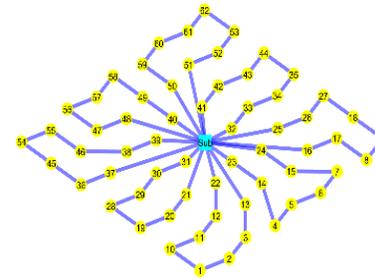
CVRP and ring ECS planning are **highly similar**
Results of CVRP naturally meet the "**N-1**" criterion

Power network expansion planning model

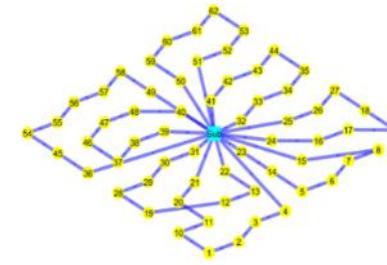
Incorporating constraints such as **DC power balance**
Using approximate methods to value the **network loss**

k-degree centrality tree (k-DCT) model

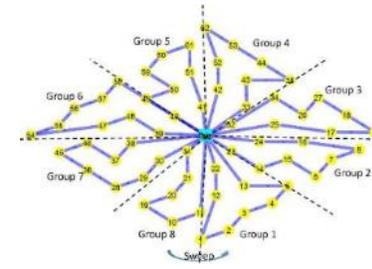
The k-DCT model is used to solve the mTSP, providing a lower bound for CVRP and not affecting the feasibility



Proposed method



Google OR-Tools



Heuristics

Optimal planning method for ring ECS

- Conform to "N-1" Principle, reducing failure losses
- No crossing cable (**outperforms Google OR-Tools**)
- Total cost reduced by 26%, with a total lifecycle of 145 M CNY (initial investment of 30 M CNY)
- Solution is highly optimal (**outperforms Google OR-Tools**)

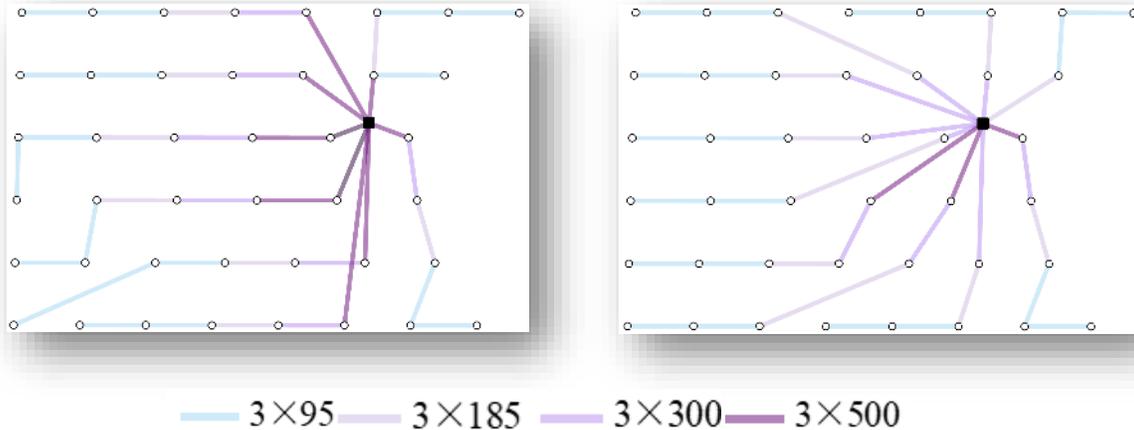
- ❑ **Key challenges:** How to consider complex constraints, economic and reliability to optimize ECS?
- ❑ **For radial topology,** a MIQP is proposed (with MILP as warm starts) considering network loss.

$$\begin{aligned} & \min F^{OW}(x^l, y) \\ & \text{s. t. } H^{OW}(x^l, y) \geq 0 \\ & \quad x^l \in D \\ & \quad G^{OW} = (E^{OW}, V^{OW}) \end{aligned}$$



$$\begin{aligned} & x^l \in \{0,1\}^{n \times n \times k}, \\ & n = |V^{OW}|: \text{Number of WTs} \\ & k: \text{Type of cables} \end{aligned}$$

Results for ECS topology and cable type selection



Original plan(Artificial experience+Heuristics software)

Proposed method^{[1][2]}

- Proposed method^{[1][2]} optimize the total length and type of cables
- In two OWFs, a total initial investment of 25 M CNY was saved, and a thanks letter was received from design institute

Received a letter of thanks from the design institute

清华大学深圳国际研究生院：

我单位于 2023 年 11 月委托贵单位沈欣炜课题组开展海上风电集电系统电压等级及拓扑规划研究，为海上风电项目优化集电线路提供技术支持。

贵单位积极支持配合我们工作，特此证明：该课题组研究成果对不同海上风电场的集电线路规划均做出了相较于传统工程规划方法经济性更优的方案，在两个风电场案例中平均可节省集电系统初始投资上千万元。该技术具有较好的推广价值，为我单位后续海上风电的开发提供了有益参考。贵单位相关科研人员沈欣炜、纪鑫哲、丁晓驰、高闻浩、陆柏安、李健等同志按时高质量完成了相关研究工作，向贵单位相关人员的支持和贡献表示感谢！

单位

2024 年



[1]X Shen*, S. Li and H. Li, "Large-scale Offshore Wind Farm Electrical Collector System Planning: an MILP Approach," in IEEE 5th Conf. on EI^2, Taiyuan, China, 2021, pp. 1248-1253.

[2] Wenhao Gao, X Shen*, et al., "Optimization planning of offshore wind electrical collector system based on large-scale mixed integer programming", in AEPS (in Chinese), 2025.

- ❑ **Key challenge:** How to optimize reliability-based ECS **without predefined topology (radial/ring)?**
- ❑ A **two-stage stochastic programming model** is presented and solved by **customized progressive contingency incorporation algorithm**.

Mathematical Model

• Objective function

$$\min \underbrace{C_{INV}}_{\text{Cable investment cost}} + \underbrace{C_{O\&M}}_{\text{Operational and maintenance cost}} + \underbrace{C_{REL}}_{\text{Wind curtailment cost due to contingencies}}$$

$$C_{INV} = C_{cab} \sum_{ij \in \Psi_C} d_{ij} l_{ij} \quad C_{O\&M} = \beta C_{INV} \quad C_{REL} = C_{ele} \frac{(1+r)^t - 1}{r(1+r)^t} U \sum_{rs \in \Psi_C \cup \{NO\}} \xi^{rs} \sum_{\omega \in \Omega} \delta^\omega \sum_{k \in \Psi_N^{WT}} P_k \zeta^\omega \frac{\tau_{SW} m_k^{rs} + \tau_{RP} n_k^{rs}}{\tau_{SW} + \tau_{RP}}$$

Parameters & Sets:

C_{cab} : per-unit cost of cable	r/t : discount ratio/lifetime of the project
d_{ij} : length of cable ij	ω/Ω : index/set for wind speed scenarios
β : ratio of O&M cost to investment cost	δ^ω : probability of ω
C_{ele} : unit price of offshore wind energy	ζ^ω : magnitude of ω
U : number of hours per year	k/Ψ_N^{WT} : index/set for wind turbines
rs/Ψ_C : index/set for cables	P_k : power generated by wind turbine k
NO : index for normal operation state	τ_{SW}/τ_{RP} : time required to isolate/repair the fault
ξ^{rs} : probability of system scenario rs	

Decision Variables:

l_{ij} : cable investment variable, 1 when cable ij is installed

m_k^{rs} : fault impact variable, 1 when wind turbine k is affected in the scenario rs

n_k^{rs} : fault continuation variable, 1 when wind turbine k still cannot send power after reconfiguration in the scenario rs

- ❑ **Key challenge:** How to optimize reliability-based ECS **without predefined topology (radial/ring)?**
- ❑ A **two-stage stochastic programming model** is presented and solved by **customized progressive contingency incorporation algorithm.**

Mathematical Model

- **Objective:**

$$\min \quad \underbrace{C_{INV}}_{\text{Cable investment cost}} + \underbrace{C_{O\&M}}_{\text{Operational and maintenance cost}} + \underbrace{C_{REL}}_{\text{Wind curtailment cost due to contingencies}}$$

- **Constraints:**

- DC Power flow constraints,
- Device capacity constraints,
- Fault impact identification constraints,
- Post-fault network reconfiguration constraints,
- Non-crossing constraint

Customized PCI algorithm

Algorithm 2 Customized PCI algorithm

Initialization:

- 1: $\tilde{\Upsilon} = v_0, \Omega = \omega_n$;
- 2: Apply BD strategy to solve $(\hat{x}, \hat{y}^{v,\omega}) = \arg \min_{x,y^{v,\omega}} \tilde{\mathcal{P}}_{\tilde{\Upsilon},\Omega}$ to $\epsilon \leq \epsilon_0$;
- 3: $\hat{\Upsilon} = \{v_i | v_i \in \Upsilon \cup v_0, \hat{x}_i = 1\}$, $x_{ws} = \hat{x}$, $Ind = 0$;

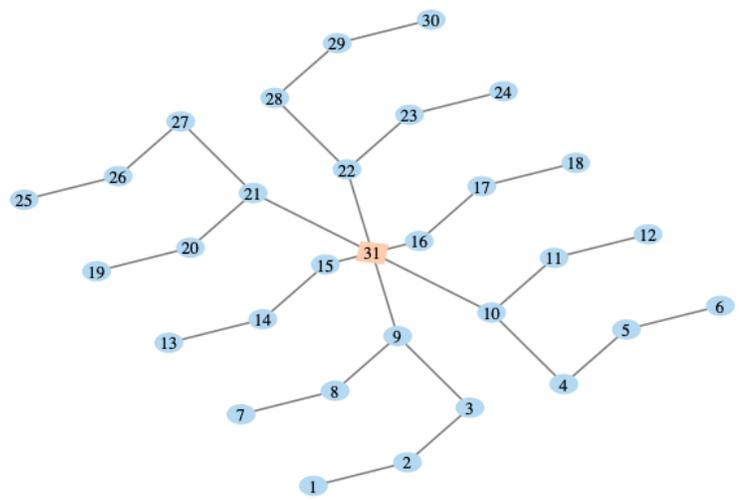
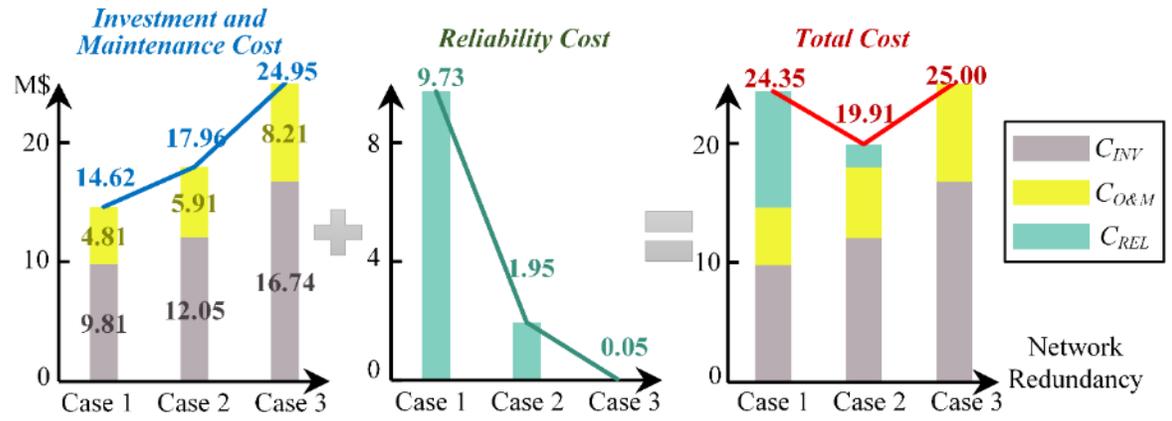
Iteration:

- 4: **while** $Ind == 0$ **do**
 - 5: $\tilde{\Upsilon} = \tilde{\Upsilon} \cup \hat{\Upsilon}$;
 - 6: Apply BD strategy to solve $(\hat{x}, \hat{y}^{v,\omega}) = \arg \min_{x,y^{v,\omega}} \tilde{\mathcal{P}}_{\tilde{\Upsilon},\Omega}$ to $\epsilon \leq \epsilon_0$ with warm-start point x_{ws} ;
 - 7: $\hat{\Upsilon} = \{v_i | v_i \in \Upsilon, \hat{x}_i = 1\} \cup v_0$, $x_{ws} = \hat{x}$;
 - 8: **if** $\hat{\Upsilon} == \hat{\Upsilon} \cap \tilde{\Upsilon}$ **then**
 - 9: Apply BD strategy to solve $(x^*, y^{v,\omega*}) = \arg \min_{x,y^{v,\omega}} \tilde{\mathcal{P}}_{\tilde{\Upsilon},\Omega}$ to optimality with warm-start point x_{ws} ;
 - 10: $\Upsilon^* = \{v_i | v_i \in \Upsilon, x_i^* = 1\} \cup v_0$;
 - 11: **if** $\Upsilon^* == \Upsilon^* \cap \tilde{\Upsilon}$ **then**
 - 12: $Ind = 1$;
 - 13: **else**
 - 14: $\tilde{\Upsilon} = \tilde{\Upsilon} \cup \Upsilon^*$, $x_{ws} = x^*$;
 - 15: **end if**
 - 16: **end if**
 - 17: **end while**
-

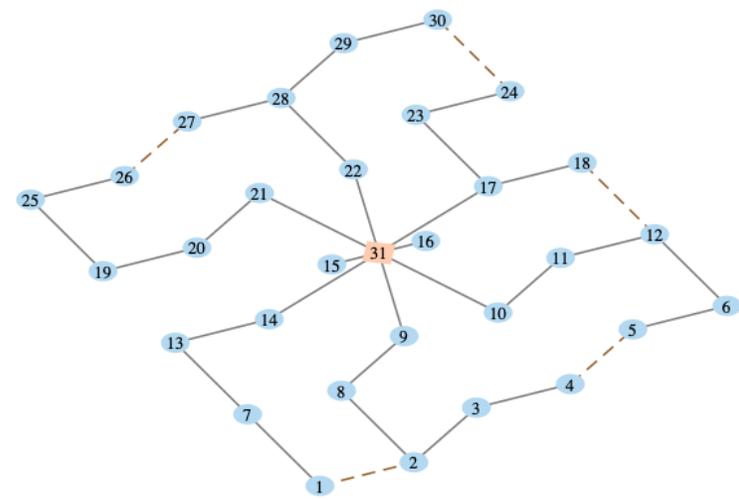
Case Study-30 WTs Case

To validate the **effectiveness** of the proposed method, the 30-WT OWF is utilized as the first benchmark.

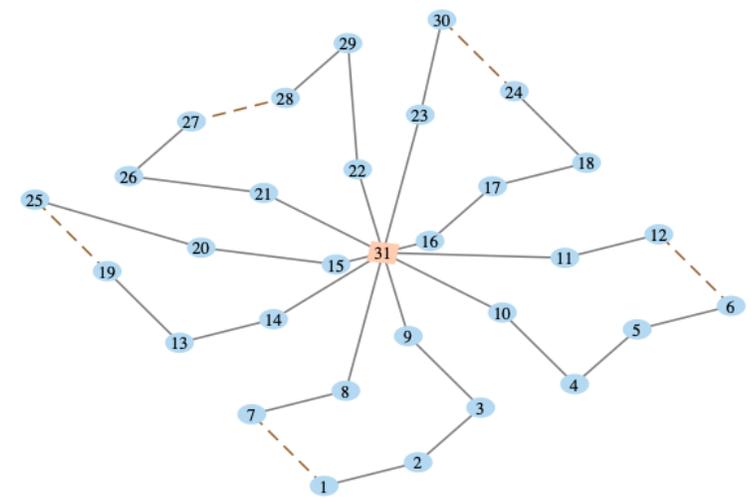
Case 1: ECS planning with radial structural limitation;
 Case 2: ECS planning without predefined structural limitation;
 Case 3: ECS planning with ring structural limitation.



(a) Case 1: Radial planning approach



(b) Case 2: Proposed planning approach



(c) Case 3: Ring planning approach

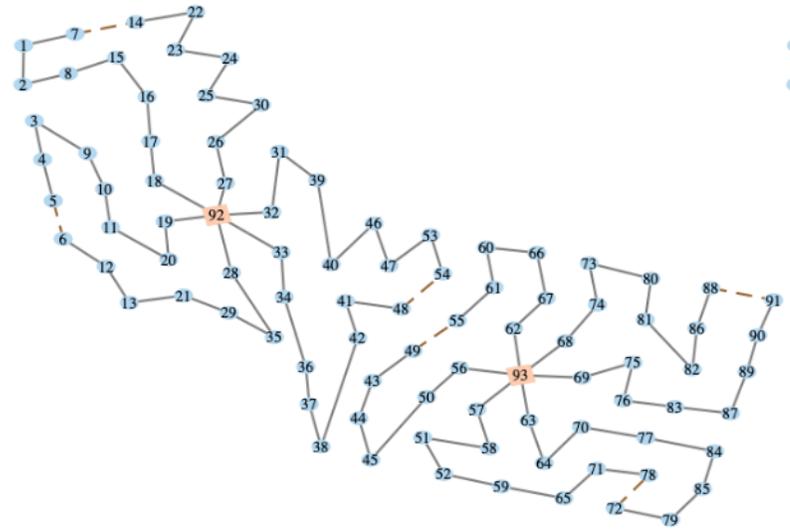


Case Study-91 WTs Case (RaceBank OWF)

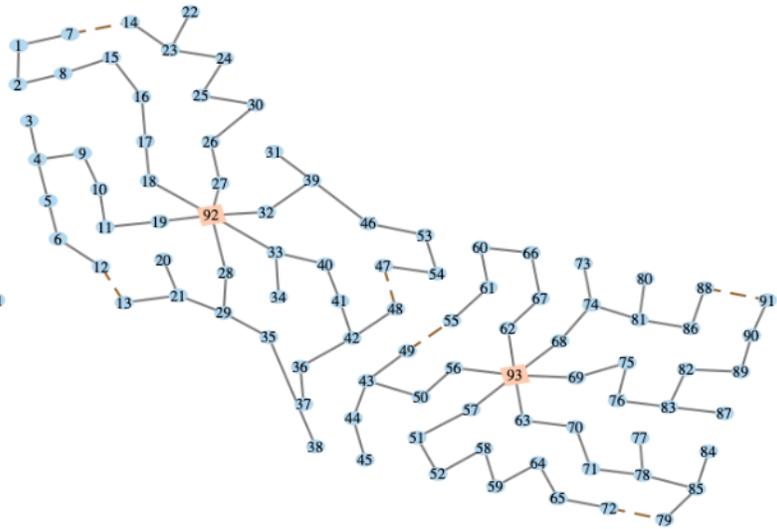
Case 4: ECS planning with two-phase CWS algorithm;
 Case 5: Proposed ECS planning without offshore substation coordination;
 Case 6: Proposed ECS planning with offshore substation coordination.

TABLE I
RACE BANK OWF ECS PLANNING RESULTS

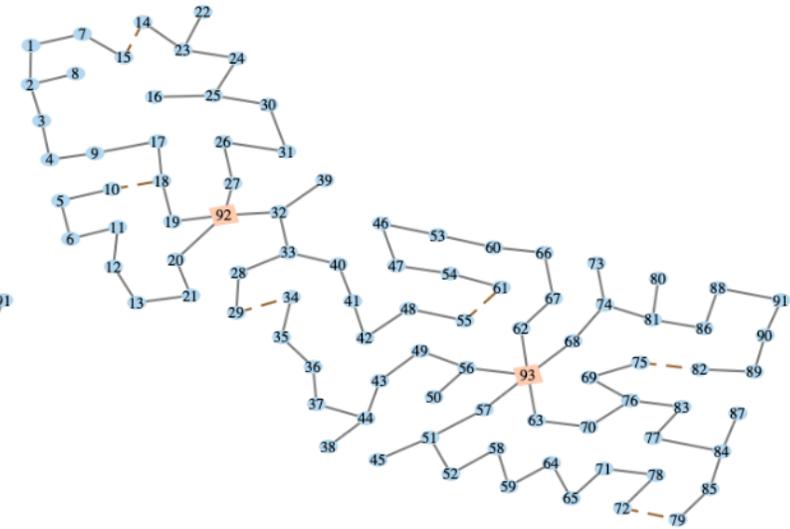
	Case 4 [24]	Case 5	Case 6
$C_{INV}(M\$)$	42.86	40.27	38.82
$C_{O\&M}(M\$)$	21.03	19.76	19.04
$C_{REL}(M\$)$	0.13	1.41	2.91
Total cost (M\$)	64.02	61.44	60.77



(a) Case 4: Sweep + CWS planning



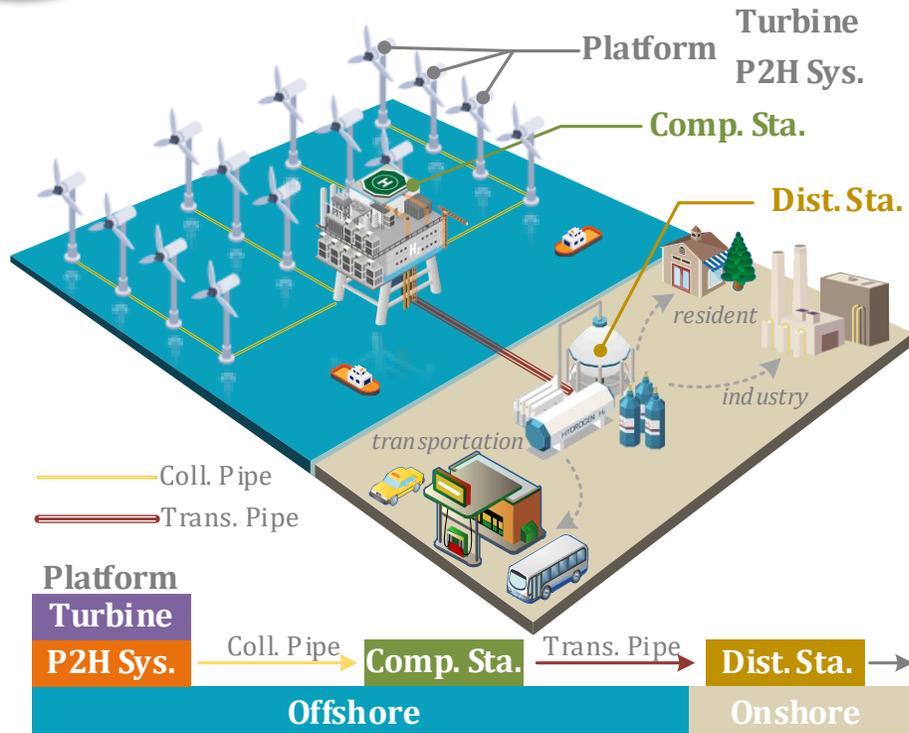
(b) Case 5: Proposed ECS planning without OSS coordination



(c) Case 6: Proposed ECS planning with OSS coordination

Key issue

How can the cost of hydrogen production from OWF be further reduced through optimization methods?



OWPHP schematic diagram

- ❑ **Hydrogen Production:** Offshore wind platforms generate electricity, converted to hydrogen via P2H systems.
- ❑ **Hydrogen Transmission:** Hydrogen is piped to a compression station for short-term storage, then transmitted ashore.
- ❑ **Hydrogen Usage:** Onshore, it's processed, compressed, and distributed for various applications.

Ideas

By optimizing different processes of OWPHP, such as **hydrogen production, conveying, and usage**, LCOH can be reduced.



□ Two stage stochastic optimization model for hydrogen production process

■ First-stage optimization model

➤ Objective: LCOH

$$\min_{\mathbb{X}, \mathbb{Y}, Q^{P2H}} LCOH = \frac{EAC(Q^{P2H}, AHP)}{AHP(\mathbb{X}, \mathbb{Y}, Q^{P2H})}$$

Equivalent annual cost (EAC)

Annual hydrogen production (AHP)

Platform location/devices capacity

➤ Constraints

$$AHP = \mathbb{E}[H_k^{P2H}(\mathbb{X}^*, \mathbb{Y}^*, Q^{P2H*})]$$

$$EAC = EAC_{INV}(Q^{P2H}) + EAC_{OM}(Q^{P2H}) + EAC_{TAX}(Q^{P2H})$$

$$EAC_{INV} = \sum_{i \in N} (R_A^{P2H} c_{INV}^{P2H} Q_i^{P2H} + R_A^{WT} c_{INV}^{WT} P_{MAX}^{WT})$$

$$EAC_{OM} = \sum_{i \in N} (c_{OM}^{P2H} Q_i^{P2H} + c_{OM}^{WT} P_{MAX}^{WT})$$

$$EAC_{TAX} = c_{TAX} (c_H AHP - AC_{OM})$$

- AHP and EAC calculation
- EAC includes investment, O&M, tax and other costs

$$\text{s.t.: } \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq 5D$$

$$x_{MIN} \leq x_i \leq x_{MAX}, \quad \forall i \in N$$

$$y_{MIN} \leq y_i \leq y_{MAX}, \quad \forall i \in N$$

$$0 \leq Q_i^{P2H} \leq P_{MAX}^{WT}, \quad \forall i \in N$$

- Platform distance
- OWF boundary
- Devices capacity

[1] Y. Du, X. Shen*, et al. "Joint Optimization of Layout and Electrolyzer Capacity for Decentralized Offshore Wind-Powered Hydrogen Production". in IEEE TII, 2025.

[2] Y. Du, X. Shen*, et al. "Capacity Optimization Configuration of Distributed Offshore Wind Power to Hydrogen Considering Micro-siting", in AEPS (in Chinese), 2024.



□ Two stage stochastic optimization model for hydrogen production process

■ Second-stage optimization model

➤ **Objective: AHP**
$$H_k^{P2H}(\mathbb{X}^*, \mathbb{Y}^*, \mathbb{Q}^{P2H*}) = \max_{\mathbb{I}_k^{P2H}} 8760 \sum_{i \in N} h_{k,i}^{P2H}(I_{k,i}^{P2H}), \forall k \in K$$

➤ Constraints

- Operation current constraint
- System capacity constraint

s.t.: $\gamma_{\text{MIN}} Q_i^{P2H} \leq I_{k,i}^{P2H} \leq \gamma_{\text{MAX}} Q_i^{P2H}, \forall k \in K, \forall i \in N$

$P_{k,i}^{P2H} \leq Q_i^{P2H}, \forall k \in K, \forall i \in N$

- Basic model:
- ✓ WT output model
- ✓ Seawater electrolysis model

$$P_i^{\text{WT}} \geq P_i^{\text{P2H}} = P_i^{\text{CON}} + P_i^{\text{DES}} + P_i^{\text{ELE}}, \forall i \in N \quad I_i^{\text{P2H}} = f(P_i^{\text{P2H}}), \forall i \in N$$

$$P_i^{\text{CON}} = \beta_2 (I_i^{\text{P2H}})^2 + \beta_1 I_i^{\text{P2H}} + \beta_0, \forall i \in N \quad P_i^{\text{DES}} = \psi^{\text{DES}} h_i^{\text{P2H}}, \forall i \in N$$

$$P_i^{\text{ELE}} = N^{\text{C}} U_i^{\text{C}} I_i^{\text{P2H}}, \forall i \in N \quad U_i^{\text{C}} = E + U_i^{\text{O}} + U_i^{\text{ACT}} \quad h_i^{\text{P2H}} = \frac{N^{\text{C}} I_i^{\text{P2H}} \eta^{\text{F}}}{2F}, \forall i \in N$$

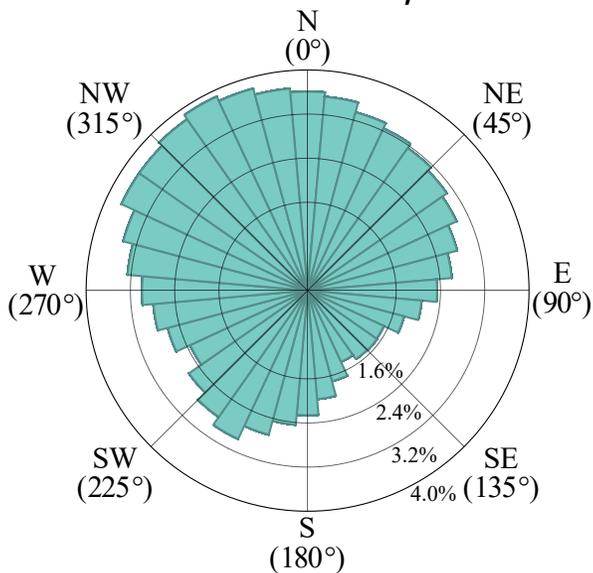
[1] Y. Du, X. Shen*, et al. "Joint Optimization of Layout and Electrolyzer Capacity for Decentralized Offshore Wind-Powered Hydrogen Production". in IEEE TII, 2025.

[2] Y. Du, X. Shen*, et al. "Capacity Optimization Configuration of Distributed Offshore Wind Power to Hydrogen Considering Micro-siting", in AEPS (in Chinese), 2024.

□ Two stage stochastic optimization model for hydrogen production process

□ Case studies:

- ✓ Set 4 cases
- ✓ Wind speed distribution: 36 wind direction scenarios, 10° interval

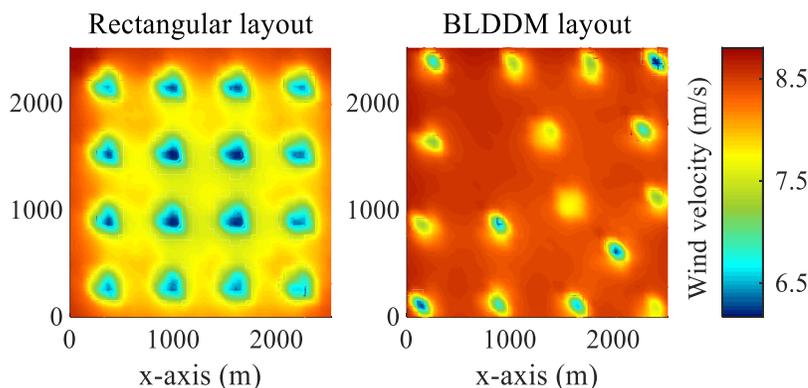


- ✓ The initial layout of the platform adopts **rectangular layout**

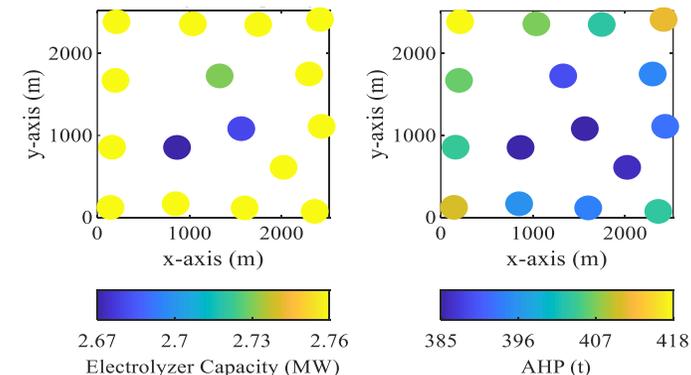
□ Platform layouts

Jointly optimized LCOH : **6.33 €/kg**

Case	Decision Variables			Simulation Results		
	Layout	Devices Capacity	Current	Annualized Cost (M€)	AHP (t)	LCOH(€/kg)
1	×	×	√	47.90	6,075.79	7.88
2	√	×	√	48.76	6,484.37	7.52
3	×	√	√	39.52	6,042.03	6.54
4	√	√	√	40.42	6,384.48	6.33



Average wind speed for different layout



Optimized electrolyzer capacity and AHP

- ✓ **Larger values at the edge and smaller values inside (capacity and AHP)**

[1] Y. Du, X. Shen*, et al. Joint Optimization of Layout and Electrolyzer Capacity for Decentralized Offshore Wind-Powered Hydrogen Production. IEEE TII, 2025.

[2] Y. Du, X. Shen*, et al. Capacity Optimization Configuration of Distributed Offshore Wind Power to Hydrogen Considering Micro-siting, AEPS, 2024.

Co-optimization model for pipeline and hydrogen gathering station

Objective Function

$$\min_{\substack{x^{GS}, y^{GS} \\ \xi_{i,j}}} C^{TPL}(x^{GS}, y^{GS}) + C^{GPL}(x^{GS}, y^{GS}, \xi_{i,j})$$

TPLs cost
GPLs cost

Investment decision variables of candidate GPL (binary variables)
Coordinates of gathering station nodes (continuous variables)

Constraints

Gathering station location range constraints

$$x^{GS} \in X, y^{GS} \in Y, (x^{GS}, y^{GS}) \in X \times Y$$

$$\text{sqrt}[(x^{GS} - x_j)^2 + (y^{GS} - y_j)^2] \leq D^{MIN}, \forall j \in V^{DP}$$

Spanning tree constraints

$$\sum_{\{i,j\} \in L} \xi_{i,j} = |V^{DP}| - 1, \quad \sum_{\{i,j\} \in L_j} \beta_{i,j} = 1, \quad \forall j \in V^{DP}$$

$$\beta_{j,i} = 0, \quad \forall i \in V^{GS}, \{i,j\} \in L, \quad \beta_{i,j} + \beta_{j,i} = \xi_{i,j}$$

Hydrogen flow balance constraints

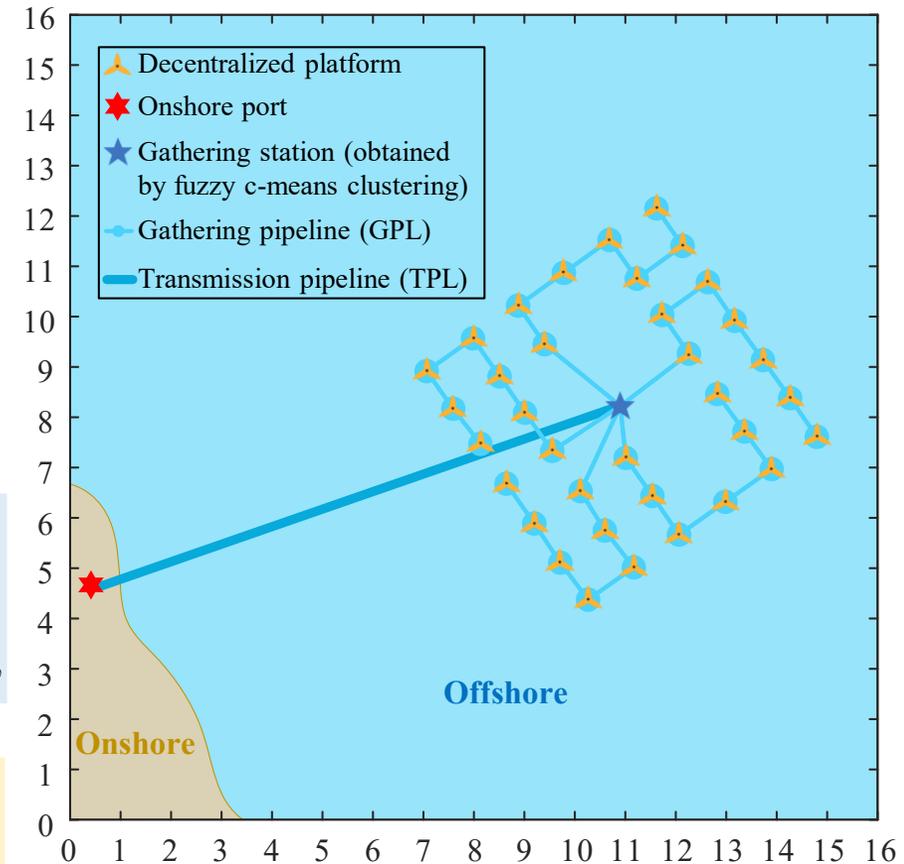
$$|F_{i,j}| \leq \xi_{i,j} \bar{F}_{i,j}, \quad \forall \{i,j\} \in L$$

$$\sum_{\{i,j\} \in L_i} F_{i,j} - H_i = \sum_{\{k,i\} \in L_i} F_{k,i}, \quad \forall i \in V^{DP}$$

Engineering constraints

$$\xi_{i,j} + \xi_{m,p} \leq 1, \quad \forall \{i,j\} \times \{m,p\} \neq \emptyset, \{i,j\}, \{m,p\} \in L$$

$$\sum_{\{i,j\} \in L_j} \xi_{i,j} \leq N, \quad \forall j \in V^{DP}, \quad \xi_{i,j} = 0, \quad \forall \text{dist}(i,j) \geq D^{MAX}$$



Topology for decentralized OWHS

□ Co-optimization model for pipeline and hydrogen gathering station

■ Two-phase optimization approach

- **The first phase** utilizes a grid-based **MILP** model to co-optimize the gathering station location and the pipeline's topology.

First Phase: Grid-based Layout Co-planning

$$\begin{aligned} \min_{\xi_{i,j}} \quad & C^{TPL}(x^{GS}, y^{GS}) + C^{GPL}(x^{GS}, y^{GS}, \xi_{i,j}) \quad \forall k \in K \\ \text{s.t.} \quad & (x^{GS}, y^{GS}) = (x_k^{GS}, y_k^{GS}), (2) - (15) \end{aligned}$$

$$(x^{GS*}, y^{GS*})$$

Coordinates of gathering station



$$\xi_{i,j}^*$$

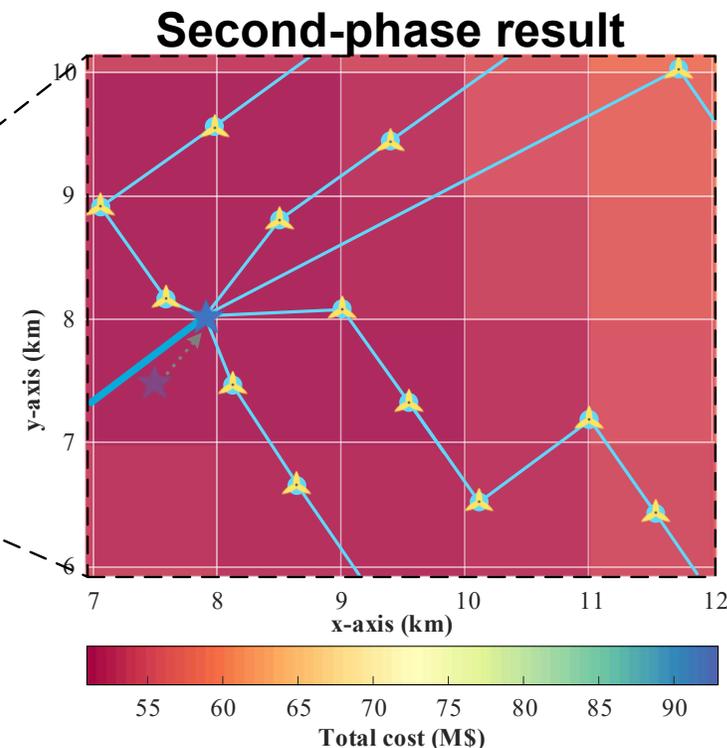
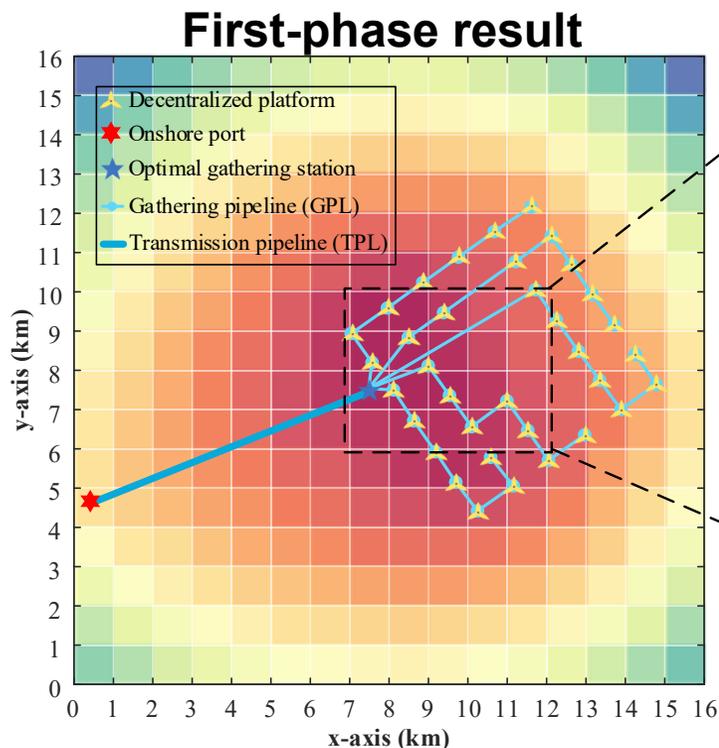
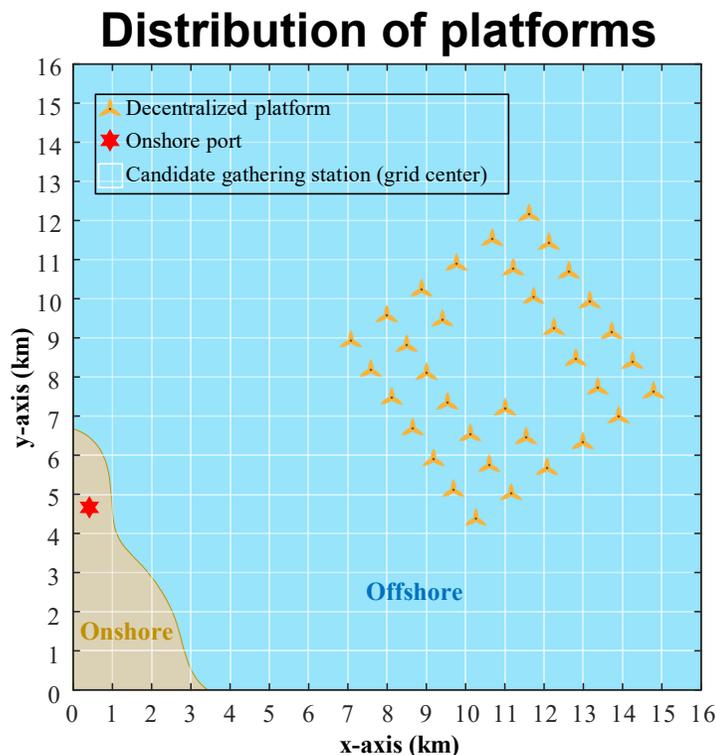
Decision variables of candidate GPI

- **The second phase** employs the sequential quadratic programming (SQP) algorithm to refine the location of the gathering station.

Second Phase: Gathering Station Location Refinement

$$\begin{aligned} \min_{x^{GS}, y^{GS}} \quad & C^{TPL}(x^{GS}, y^{GS}) + C^{GPL}(x^{GS}, y^{GS}, \xi_{i,j}) \\ \text{s.t.} \quad & \xi_{i,j} = \xi_{i,j}^*, (x_{(0)}^{GS}, y_{(0)}^{GS}) = (x^{GS*}, y^{GS*}), (2) - (15) \end{aligned}$$

□ Co-optimization model for pipeline and hydrogen gathering station

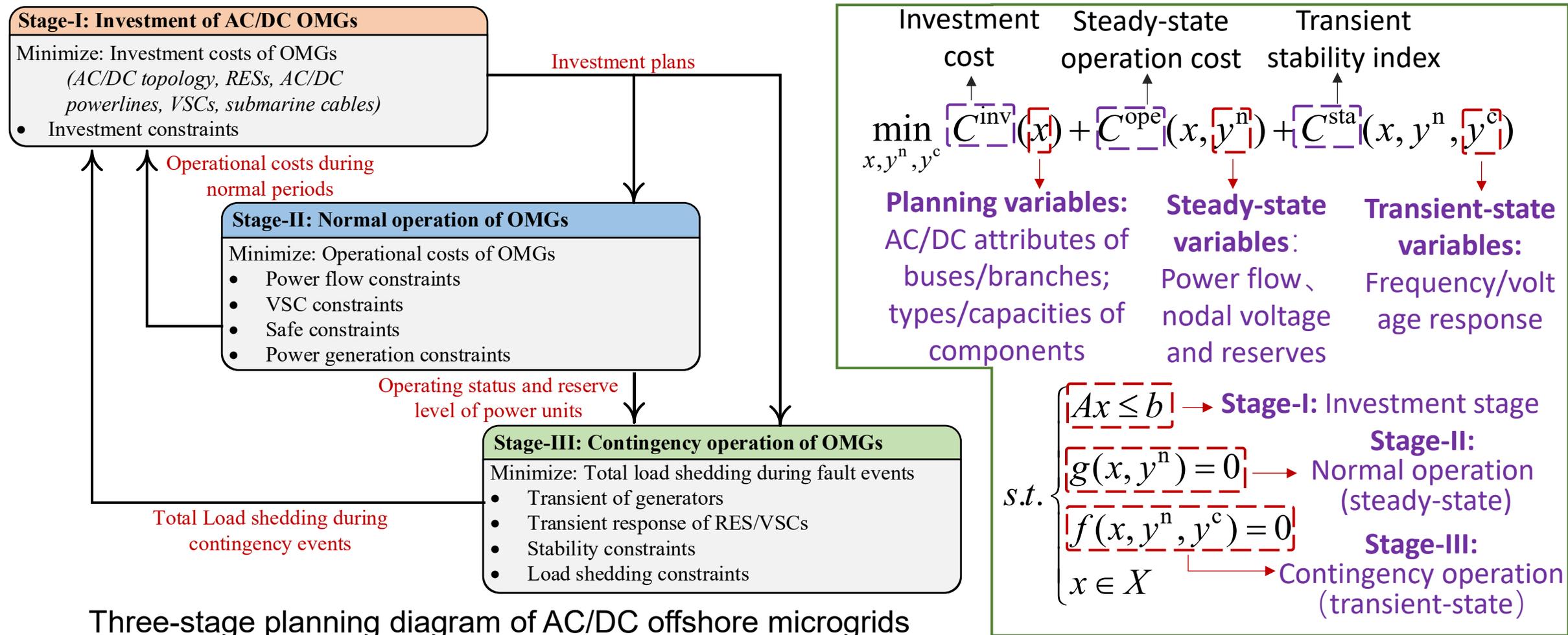


- **First-phase optimized results:** When the gathering station is placed at the edge of the site near the shoreline, the total cost is generally lower. The gathering station location with the lowest cost is (7,500 m, 7,500 m).
- **Second-phase optimized results:** The location of the hydrogen gathering station is refined to (7,896 m, 8,004 m), reducing the inherent error caused by the gridding.

[1] Y. Du, X. Shen*, et al. A mathematical programming approach to export pathway planning of distributed hydrogen production in offshore wind farm. IJOHE, 81, pp.753-764, 2024.

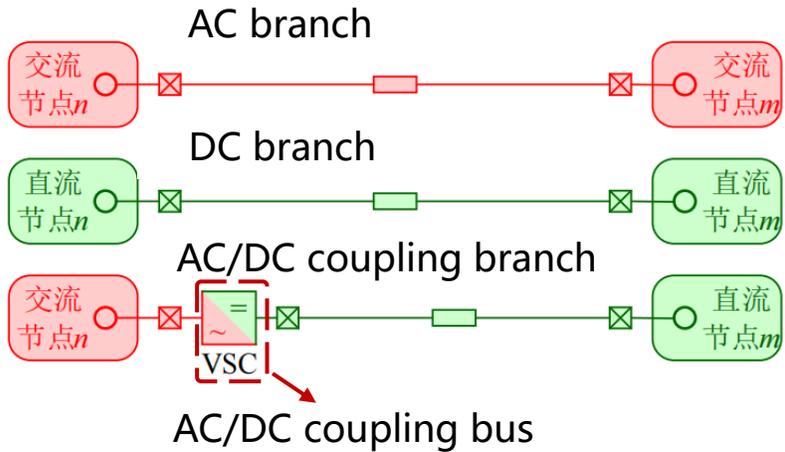
[2] Y. Du, X. Shen*, et al. Pipeline Network Layout, X. Planning for Decentralized Offshore Wind-Hydrogen System: A Two-Phase Optimization Approach. IEEE PES General Meeting, 2025.

Three-stage planning framework of AC/DC offshore microgrids



□ Three-stage decision modelling

■ Stage-I: Investment stage



$$y_{l,id}^{AC} \geq \max\{x_{b_l^+,id}^{AC}, x_{b_l^-,id}^{AC}\}, \forall l \in \Omega_{id}^{LN}, id \in \Omega^{ID}$$

$$y_{l,id}^{DC} \geq \max\{x_{b_l^+,id}^{DC}, x_{b_l^-,id}^{DC}\}, \forall l \in \Omega_{id}^{LN}, id \in \Omega^{ID}$$

$$y_{l,id}^{AC} + y_{l,id}^{DC} = 1, \forall l \in \Omega_{id}^{LN}, id \in \Omega^{ID}$$

$$x_{b,id}^{AC} + x_{b,id}^{DC} + x_{b,id}^{AD} = 1, \forall b \in \Omega_{id}^B, id \in \Omega^{ID}$$

Logic constraints for AC/DC bus/branch decision and identification

■ Stage-II: Normal operation

■ Unified AC/DC branch model

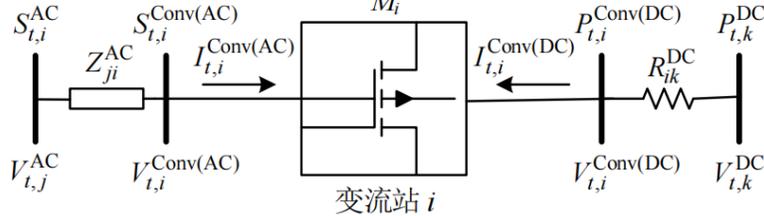
$$P_{l,id,t}^{LN} = g_{l,id} \sum_{b \in \Omega_{id}^B} K_{b,l,id}^{LN} (y_{l,id}^{AC} u_{b,id,t}^{AC} + y_{l,id}^{DC} u_{b,id,t}^{DC}) - b_{l,id} \theta_{l,id,t}^{LN}$$

$$Q_{l,id,t}^{LN} = -b_{l,id} \sum_{b \in \Omega_{id}^B} K_{b,l,id}^{LN} (y_{l,id}^{AC} u_{b,id,t}^{AC} + y_{l,id}^{DC} u_{b,id,t}^{DC}) - g_{l,id} \theta_{l,id,t}^{LN}$$

■ VSC model:

$$M(x_{b,id}^{AD} - 1) \leq u_{b,id,t}^{AC} - K^{VSC} M_{b,id}^{VSC} u_{b,id,t}^{DC} \leq M(1 - x_{b,id}^{AD})$$

$$(P_{b,id,t}^{VSC})^2 + (Q_{b,id,t}^{VSC})^2 \leq (S_{b,id}^{VSC})^2, \forall b \in \Omega_{id}^B, id \in \Omega^{ID}$$



■ Generator, wind /PV constraints

■ Island-specific components: electric vessels, desalination and hydrogen production

■ Stage-III: Contingency operation

■ Rotor motion equation:

$$-M \lambda_{g,id,c}^G \leq 2H_{g,id} (f_{g,id,t+1,c}^G - f_{g,id,t,c}^G) / \Delta tn + D_{g,id} \Delta f_{g,id,t,c}^G - P_{g,id,t,c}^{G,m} + P_{g,id,t,c}^{G,e} \leq M \lambda_{g,id,c}^G, \forall g \in \Omega_{id}^G$$

■ AC/DC transient response :

$$A_{g,id,t+1,c}^G = A_{g,id,t,c}^G + (-\kappa_{g,id}^G \Delta f_{g,id,t,c}^G - A_{w,id,t,c}^G) / T_{g,id}^G$$

$$A_{w,id,t,c}^{WT1} = x_{b_w,id}^{DC} \times (-\Delta u_{b_w,id,t,c}^{DC,c} \kappa_{w,id}^{WT,v}) + (1 - x_{b_w,id}^{DC}) \times \{-\Delta f_{b_w,id,t,c}^{WT,f} + 2H_{w,id}^{WT} (f_{b_w,id,t+1,c} - f_{b_w,id,t,c}) / \Delta tn\}$$

■ Frequency/voltage stability:

$$\Delta f_{b,id,t,c} = f_{b,id,t,c} - f^{ref}, \forall b \in \Omega_{id}^B, tn \in \Omega_c^{TN}$$

$$-\Delta f^{max} \leq \Delta f_{b,id,t,c} \leq \Delta f^{max}, \forall g \in \Omega_{id}^G$$

$$|(\Delta f_{b,id,t+1,c} - \Delta f_{b,id,t,c}) / \Delta tn| \leq RoCoF^{max}$$

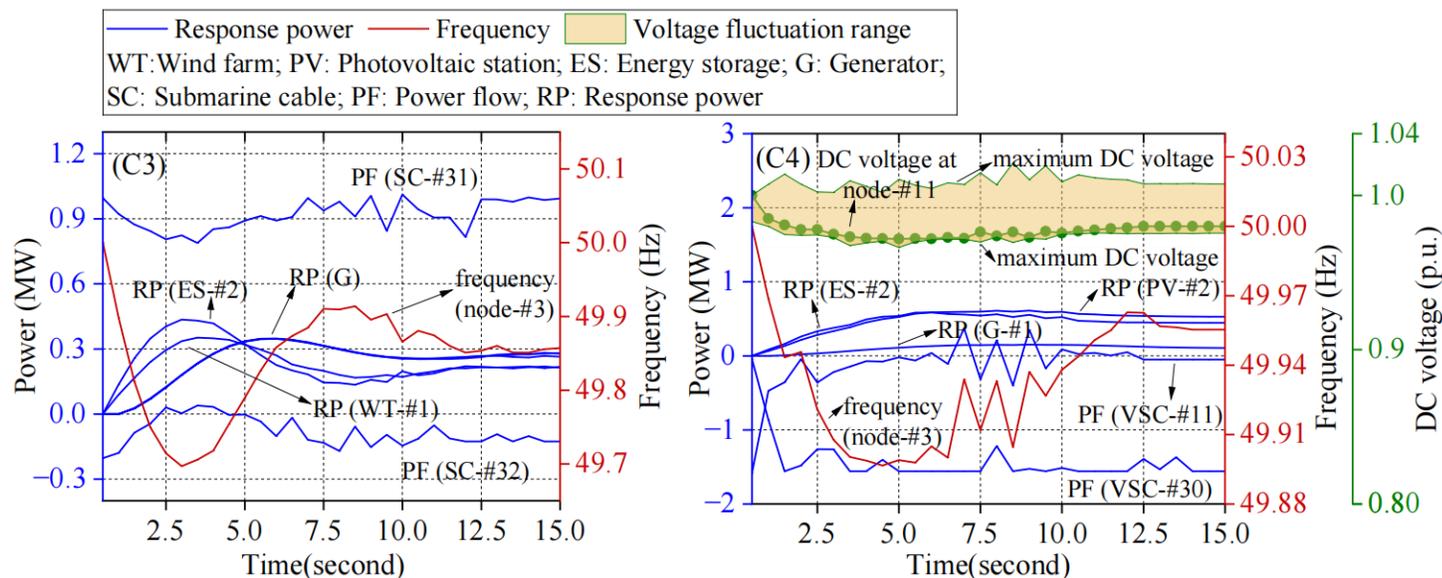
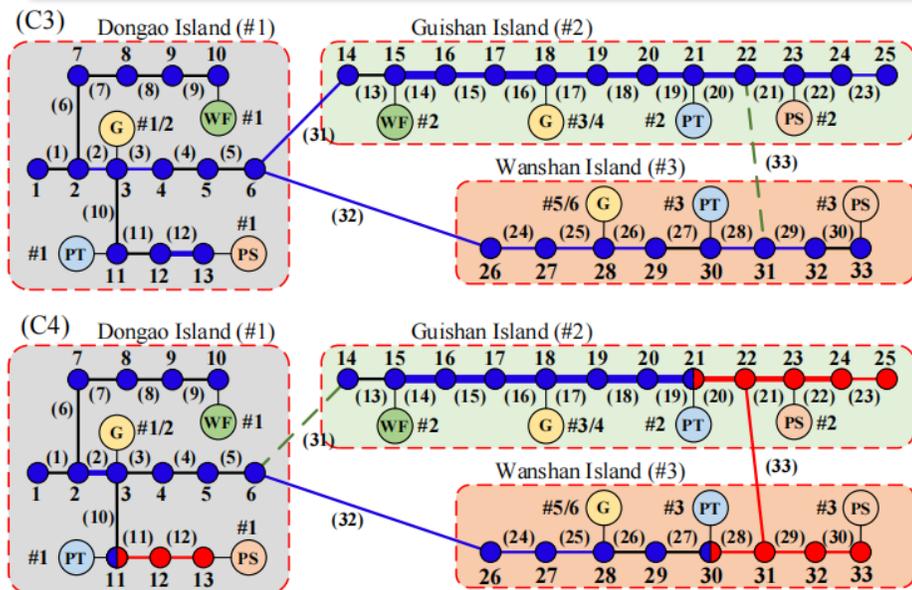
$$u_{b,id,t}^{DC,min} (1 - x_{b,id}^{AC}) \leq u_{b,id,t}^{DC} \leq u_{b,id,t}^{DC,max} (1 - x_{b,id}^{AC})$$

■ Normalized droop control of VSCs:

$$\Delta f_k = (NV_{dc_k} - Nf_k) G_{fk}$$

□ Numerical study

- A case study is conducted on a three-island AC/DC interconnected system.

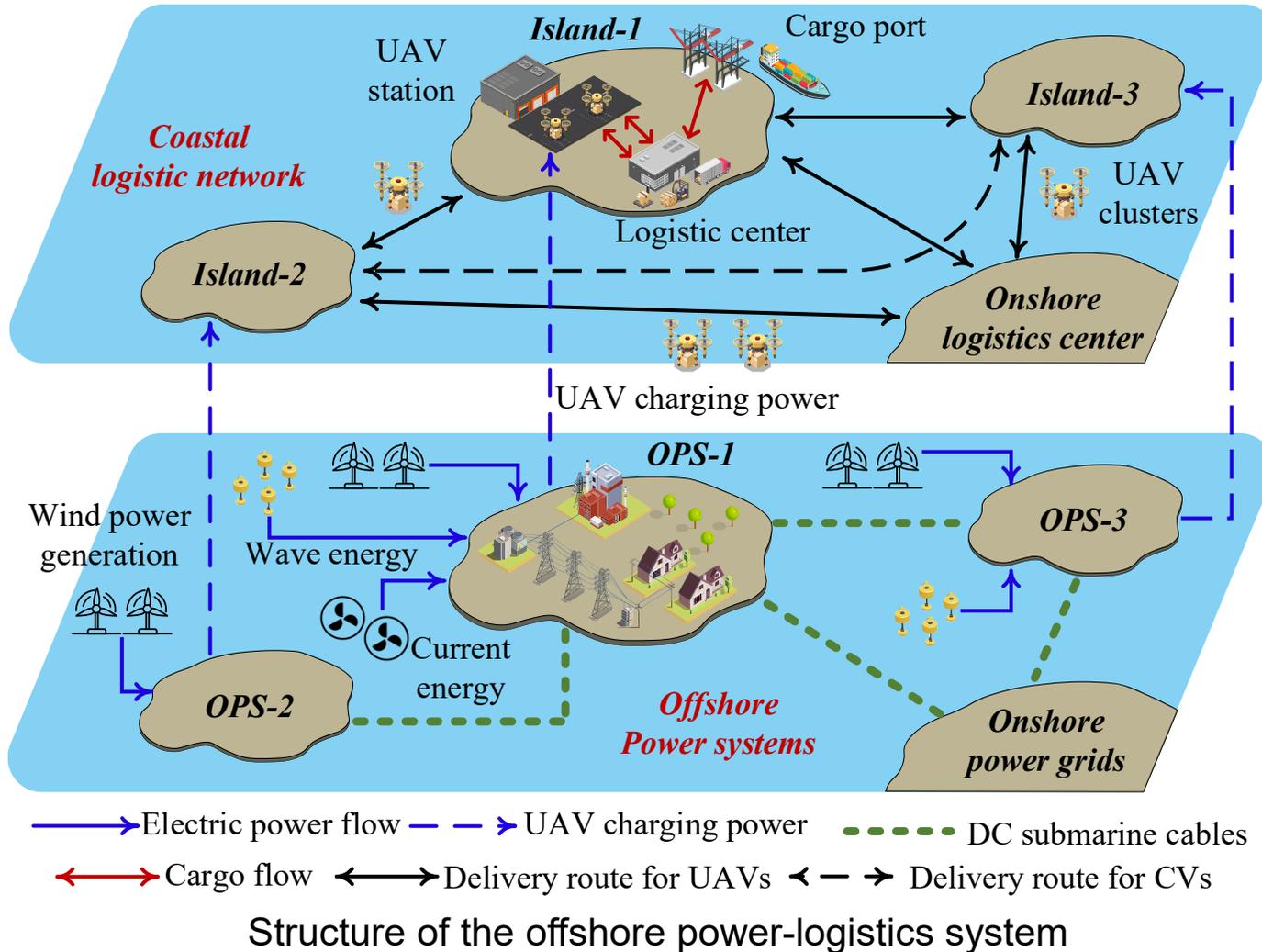


Topology of AC and AC/DC offshore microgrids

Transient response under the two system configurations

- The proposed model captures the transient response characteristics of individual components, thereby characterizing the system's frequency/voltage stability performance.
- Through **AC/DC hybrid interconnection**, the system planning cost can be reduced by **8.2%**.
- Through **multi-island submarine cable interconnection**, the offshore microgrids can **share inertia and regulation resources**, thereby exhibiting **enhanced transient stability**.

UAV-empowered coastal logistics system



① UAV-empowered coastal logistics system

$$\delta_{v,r,t}^{\text{dep}} \leq \min \left\{ \phi_{v,n_r^-,t+T_{v,r}^R}, \phi_{v,n_r^+,t} \right\}, \forall v \in \Omega^V, r \in \Omega^R$$

$$\delta_{v,r,t}^{\text{dep}} \leq 1 - \sum_{n \in \Omega^N} \phi_{v,n,\tau}, \forall \tau \in [t+1, t+T_{v,r}^R - 1], t \in \Omega^T$$

UAV delivery routing constraints

$$m_{v,u,t}^V = m_{v,u,t-1}^V + \sum_{n \in \Omega^N} m_{v,n,u,t}^{\text{upl}} - \sum_{n \in \Omega^N} m_{v,n,u,t}^{\text{unl}}$$

$$\sum_{t=1}^{t_u^{\text{des}}} \sum_{v \in \Omega^V} m_{v,n,u,t}^{\text{unl}} = \sum_{t=1}^{t_u^{\text{des}}} \sum_{n' \in \Omega^N} (m_{n',u,t}^{\text{D0}} - m_{n',u,t}^{\text{D,uns}})$$

UAV payloads and quality of service constraints

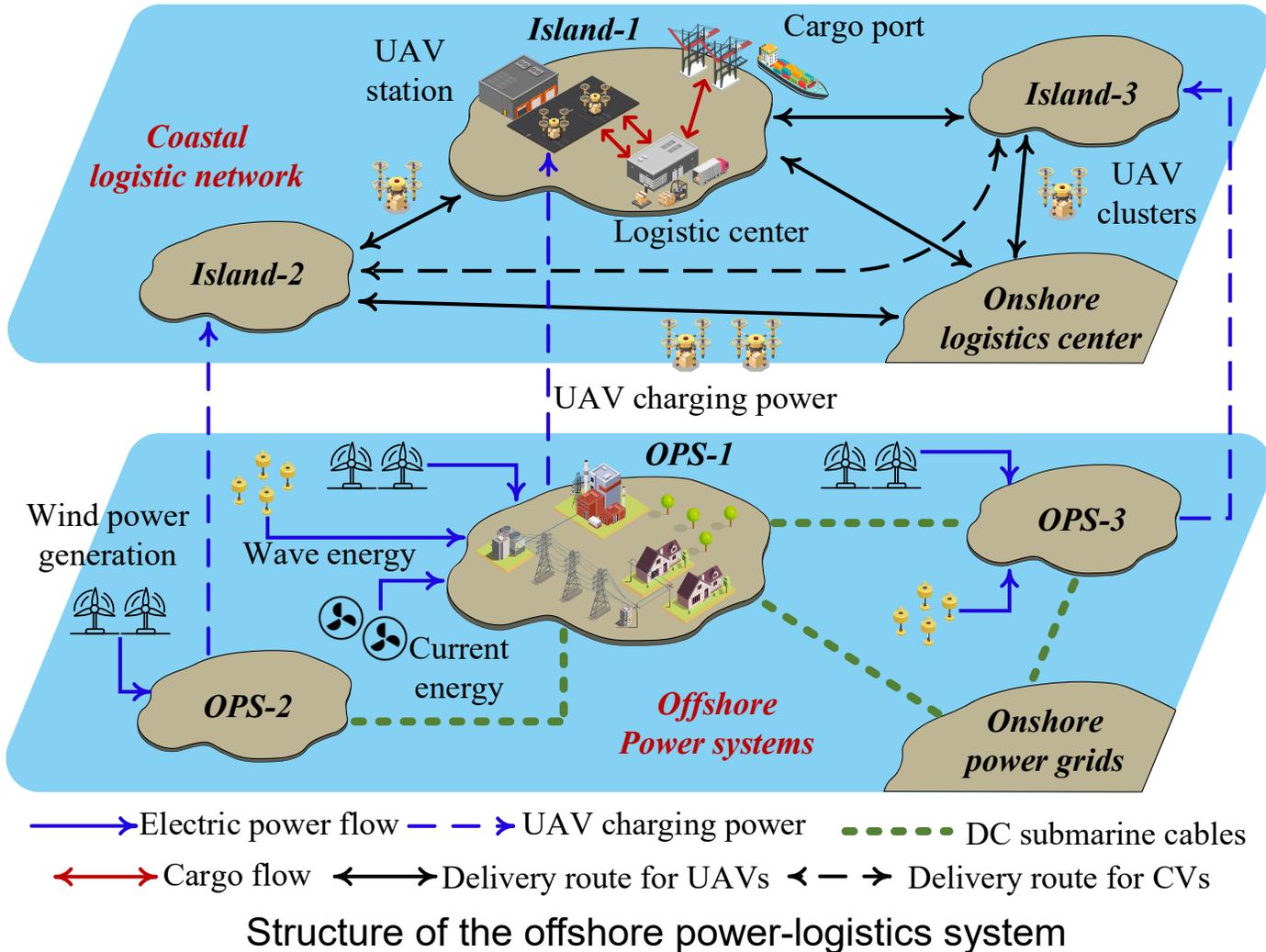
$$P^U(m^{\text{VT0}}, v^{\text{RU0}}, \gamma^U) = 0.5 \underbrace{\rho^a c^a A^U (v^{\text{RU0}})^3}_{p^{\text{air}}} + \underbrace{\kappa^U \overline{\omega}^U T^U}_{p^{\text{lift}}} + \underbrace{\rho^a R^U \sigma^U c^{\text{bd}} [(v^t)^3 + 3(v^{\text{RU0}})^2 v^t]}_{p^{\text{profile}}} / 8 + \underbrace{m^{\text{VT0}} G v^{\text{RU0}} \sin \gamma^U}_{p^{\text{climb}}} + P^{\text{int}}$$

Energy consumption constraints under marine meteorological environment

$$0 \leq P_{v,t,s}^{\text{uch}} \leq \delta_{v,t}^{\text{uch}} P^{\text{uchr}} x_v^{\text{UAV}} N^{\text{clus}}$$

UAV charging constraints

Offshore power-logistics system dispatch



Offshore power-logistics system dispatch

$$\min \sum_{id \in \Omega^{ID}} \sum_{tr \in \Omega_{id}^{TR}} \sum_{t \in \Omega^T} c_t^{ele} P_{tr,id,t}^{GD} \Delta t + c^{D,uns} \sum_{n \in \Omega^N} \sum_{u \in \Omega^U} \sum_{t \in \Omega^T} m_{n,u,t}^{D,uns} +$$

$$\left\{ \begin{array}{l} \underbrace{c^G \sum_{id \in \Omega^{ID}} \sum_{g \in \Omega_{id}^G} \sum_{t \in \Omega^T} P_{g,id,t,s}^G \Delta t}_{\text{f3: generation costs}} + \underbrace{c^{ds} \sum_{v \in \Omega^V} \sum_{t \in \Omega^T} \sum_{r \in \Omega^R} V_{v,r,t,s}^{tra}}_{\text{f4: fuel costs of CVs}} + \\ \underbrace{c^{deg} \sum_{v \in \Omega^V} \sum_{t \in \Omega^T} (P_{v,t,s}^{uch} \Delta t + \sum_{r \in \Omega^R} E_{v,r,t,s}^{tra})}_{\text{f5: battery degradation cost of UAVs}} + \\ \underbrace{c^{D,curt} \sum_{id \in \Omega^{ID}} \sum_{b \in \Omega_{id}^B} \sum_{t \in \Omega^T} P_{b,id,t,s}^{D,curt} \Delta t}_{\text{f6: Power shortage penalty cost}} + \underbrace{c^{emi} \Delta \varphi_s}_{\text{f7: carbon penalty cost}} \end{array} \right\}$$

$$\varphi_s^{LN} = \rho^{ds} \sum_{v \in \Omega^V} \sum_{r \in \Omega^R} \sum_{t \in \Omega^T} V_{v,r,t,s}^{tra}, \forall s \in \Omega^S$$

$$\varphi_{id,s}^{PS} = \left(\sum_{tr \in \Omega_{id}^{TR}} \sum_{t \in \Omega^T} \rho_{tr,id,t}^{GD} P_{tr,id,t}^{GD} + \sum_{g \in \Omega_{id}^G} \sum_{t \in \Omega^T} \rho_{g,id,t}^G P_{g,id,t,s}^G \right) \Delta t$$

$$\Delta \varphi_s \geq \max \left\{ \varphi_s^{LN} + \sum_{id \in \Omega^{ID}} \varphi_{id,s}^{PS} - \varphi^{cap}, 0 \right\}, \forall s \in \Omega^S$$

System carbon emission constraints

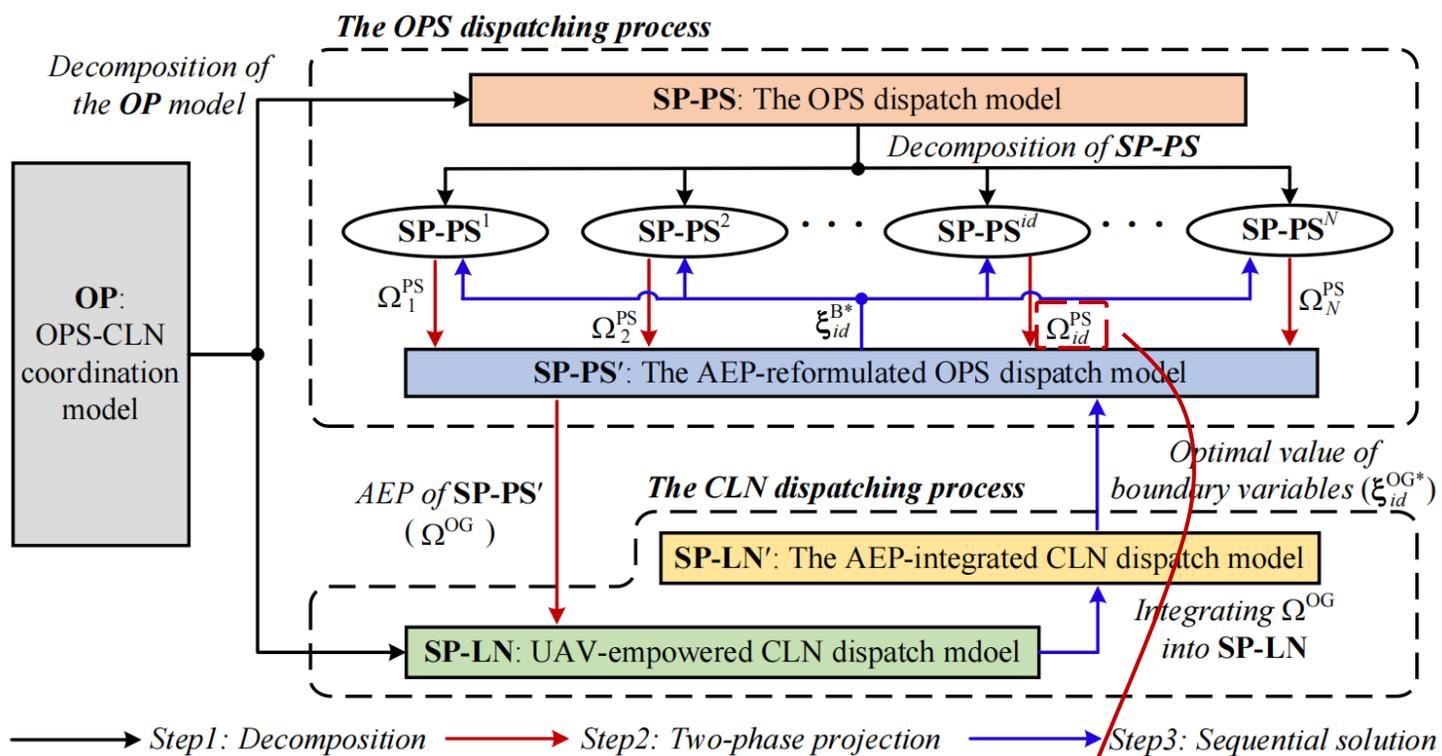
$$0 \leq P_{w,id,t,s}^{WT} \leq \min \left\{ \omega_{w,id}^{WT} (\xi_{w,id,t,s}^{wd})^3, P_{w,id}^{WT} \right\} \times \mathcal{G}_{w,id}^{WT}$$

$$0 \leq P_{h,id,t,s}^{WA} \leq \min \left\{ \omega_{h,id}^{WA} (H_{h,id,t,s}^{wa})^2 T_{h,id,t,s}^{wa}, P_{h,id}^{WA} \right\} \times \mathcal{G}_{h,id}^{WA}$$

$$0 \leq P_{j,id,t,s}^{CU} \leq \min \left\{ \omega_{j,id}^{CU} (\xi_{j,id,t,s}^{cu})^3, P_{j,id}^{CU} \right\} \times \mathcal{G}_{j,id}^{CU}$$

Marine renewables constraints

Decentralized solution approach



The overall framework of proposed solution approach

$$\Omega_{id}^{PS} := \left\{ \xi_{id}^B \mid A_{id}^{PS} \xi_{id}^B - b_{id}^{PS} \leq \mathbf{0} \right\}$$

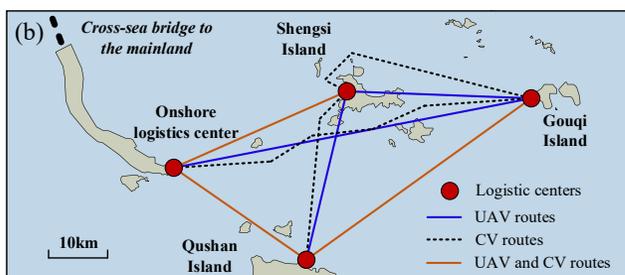
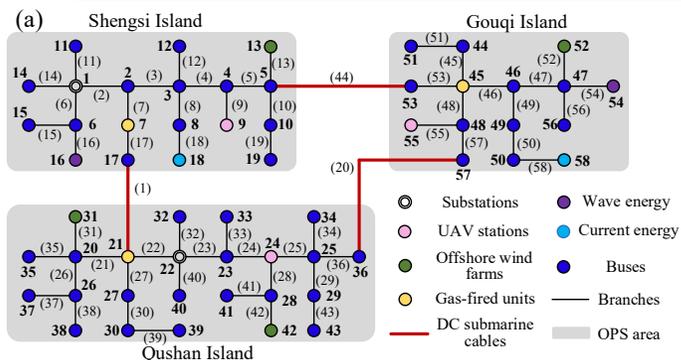
Only including boundary variables between offshore power systems and the coastal logistics system.

③ Two-phase projection-based approach

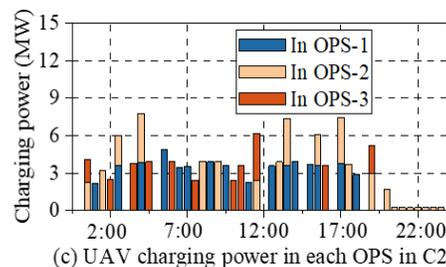
- The coordination model is solved in a decentralized manner, which ensures discretion independence and privacy security of offshore power systems and coastal logistics network.
- Different from ADMM-based approach, it involves no iteration process, which achieves a better solution efficiency and avoids convergence issue induced by binary variables.
- It is also widely applicable for coordination of various forms of interconnected multi-area grids and logistics networks

Numerical study

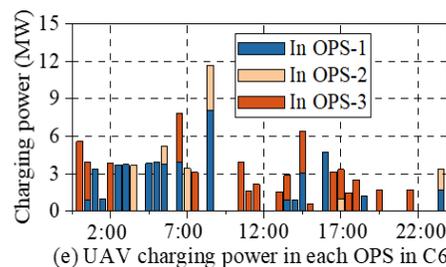
- The numerical studies are conducted based on an offshore power-logistics system located in the Zhoushan Archipelago.



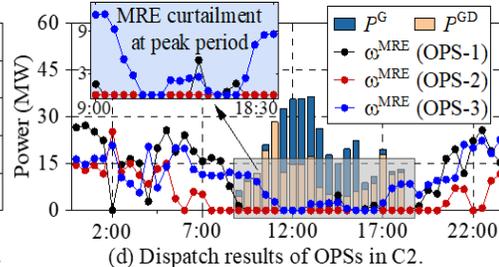
Tested offshore power-logistics system



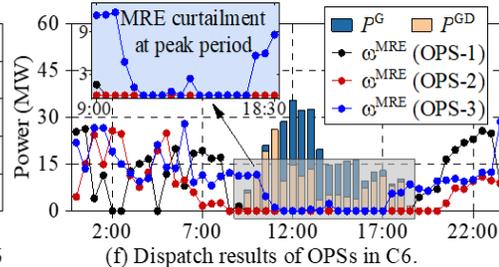
(c) UAV charging power in each OPS in C2



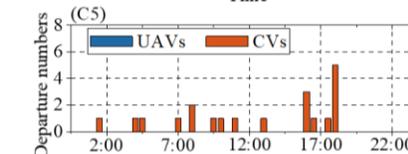
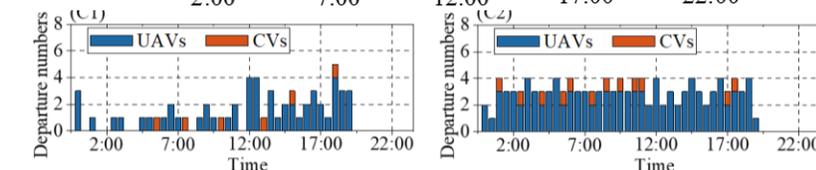
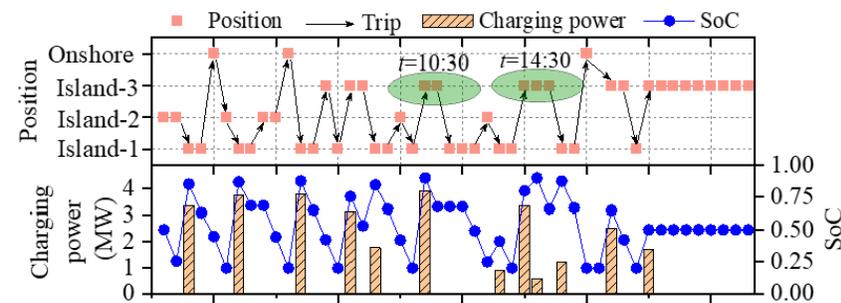
(e) UAV charging power in each OPS in C6



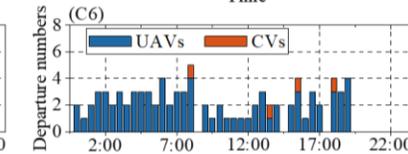
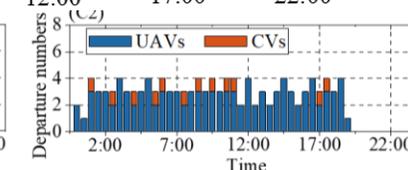
(d) Dispatch results of OPSs in C2.



(f) Dispatch results of OPSs in C6.



(C1) UAV departure dispatch results



(C3) UAV departure dispatch results

Energy dispatch results

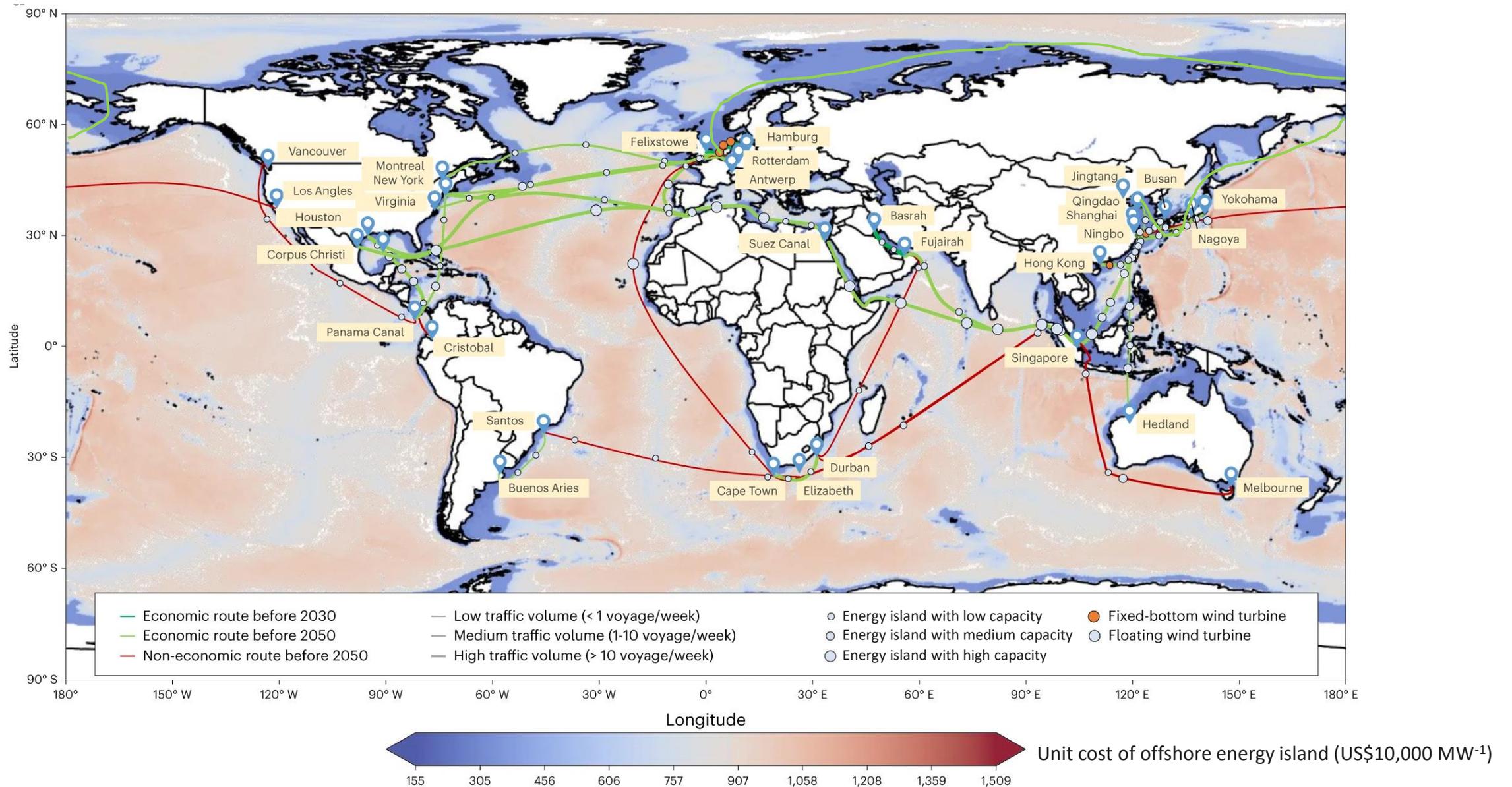
UAV departure dispatch results

- ✓ Coordinative dispatch of OPSs and CLN can effectively enhance MRE utilization and reduce total costs and carbon emissions of the OPLS. Compared to energy-oriented strategy and service quality-oriented strategy, OPS-CLN coordination achieves a 16.41% and 24.58% saving in total operating costs, and a 17.73% and 21.92% reduction in carbon emissions.
- ✓ The proposed solution method shows approving solution efficiency and accuracy, which ensures decision independence and privacy security of OPSs and the CLN.

◆ Selected papers

- [1] **X. Shen**, S. Li and H. Li, "Large-scale Offshore Wind Farm Electrical Collector System Planning: An MILP Approach," *EA'22*, Taiyuan, China, 2021, pp. 1248-1253
- [2] **X. Shen**, Qiuwei Wu, H. Zhang and L. Wang, "Optimal Planning for Electrical Collector System of Offshore Wind Farm with Double-sided Ring Topology," in *IEEE Trans. on Sustainable Energy*, 2023.
- [3] Xiaochi Ding, **X. Shen***, et al, "A Smart Switch Configuration and Reliability Assessment Method for Offshore Wind Farm ECS," *MPCE*, 2024.
- [4] Xiaochi Ding, **X. Shen***, et al, "Reliability-Based Planning of Cable Layout for Offshore Wind Farm Electrical Collector System Considering Post-Fault Network Reconfiguration" ,in *IEEE Trans. on Sustainable Energy*, 2024.
- [5] Boan Lu, **X. Shen***, et al , " Offshore Wind Farm Micro-siting based on Two-Phase Hybrid Optimization " ,in *Applied Energy*, 2025.
- [6] Y. Du, **X. Shen***, et al. Cost-competitive offshore wind-powered green methanol production for maritime transport decarbonization. *Nature Communications*, 2025.
- [7] Yufei Du, **X. Shen***, et al. Joint Optimization of Layout and Electrolyzer Capacity for Decentralized Offshore Wind-Powered Hydrogen Production. *IEEE Trans. on Industrial Informatics*, 2025.
- [8] Yufei Du, **X. Shen***, et al. Capacity Optimization Configuration of Distributed Offshore Wind Power to Hydrogen Considering Micro-siting, AEPS, 2024.
- [9] Yufei Du, **X. Shen***, et al. A mathematical programming approach to export pathway planning of distributed hydrogen production in offshore wind farm. *International Journal of Hydrogen Energy*, 81, pp.753-764, 2024.
- [10] W. Gao, **X. Shen***, etc., Optimization planning of offshore wind power collection system based on large-scale mixed integer programming, AEPS, 2025.
- [11] Yangfan Luo, **X. Shen***, et al. A Collaborative Framework for Stability-aware Expansion Planning of Offshore AC/DC Microgrids with Electrified Maritime Transport. *Ocean*, 1(1): 9470011 , 2025.
- [12] Yangfan Luo, **X. Shen***, et al. Decentralized Coordination for Offshore Power Systems and UAV-Empowered Coastal Logistics Networks. *IEEE Transactions on Sustainable Energy*, 2025.
- [13] Zehai Huang, **X. Shen***, etc., Two-Phase Micro-siting for Offshore Wind Farms with Regular Layout, submitted to *Applied Energy*, R1.

Future : Global Offshore Energy Internet





清华大学深圳国际研究生院
Tsinghua Shenzhen International Graduate School

IEEE Power & Energy Society International Meeting
JAN 21, 2026



Power & Energy Society®
INTERNATIONAL MEETING
2026

In math we trust, in application we trust



Thanks!
Welcome to follow:
www.xinweishen.com



Target: Write papers on the blue ocean!

Thanks to NSFC/Guangdong/Excellent Youth Research Fund of Shenzhen!

To Yunfei (云飞)、Yangfan (旻凡)、Xiaochi (晓驰)、Boan (柏安)、
Wenhao (闻浩)、Zehai (泽海) etc for their contributions.