清華大學深圳国际研究生院
Tsinghua Shenzhen International Graduate School

Stanford University, SPE Talk
August 1, 2025

Offshore Wind-powered Green Methanol Production for Maritime Transport Decarbonization and Some Related Optimization Methods

Xinwei Shen

Tsinghua Shenzhen International Graduate School

SIGS AT A GLANCE

Location

Tsinghua University

- 12th on THE World University Rankings list (2024)
- 1st in Asia according to the Academic Ranking of World Universities (ARWU) 2023
- Located in Beijing
- Its predecessor, "Tsing Hua Imperial College," was founded in 1911
- An important base for high-level talent cultivation and scientific research in China

Tsinghua Shenzhen International Graduate School

- Referred as "China's Silicon Valley"
- Located in Shenzhen
- Headquarters locations of high-tech companies such as Tencent, DJI, and Huawei
- Vanguard of China's reform and opening-up
- Considered as the Most Economically Vibrant City in China

Features

By diversifying faculty and student bodies, engaging in high-level collaboration with overseas partners, and internationalizing campus resources, Tsinghua SIGS will cultivate students' **global competencies** and nurture them as future global leaders.

By transcending boundaries between academic disciplines, industry and the surrounding community, Tsinghua SIGS will openly share resources and expertise to develop interdisciplinary solutions for **global challenges** beyond its physical location.

Tsinghua SIGS brings innovation to graduate education by exploring new forms of pedagogy and restructuring its administrative systems. We also offer opportunities for cooperation with industry and government organizations and provide innovative degrees to **meet rapidly changing industry needs**.

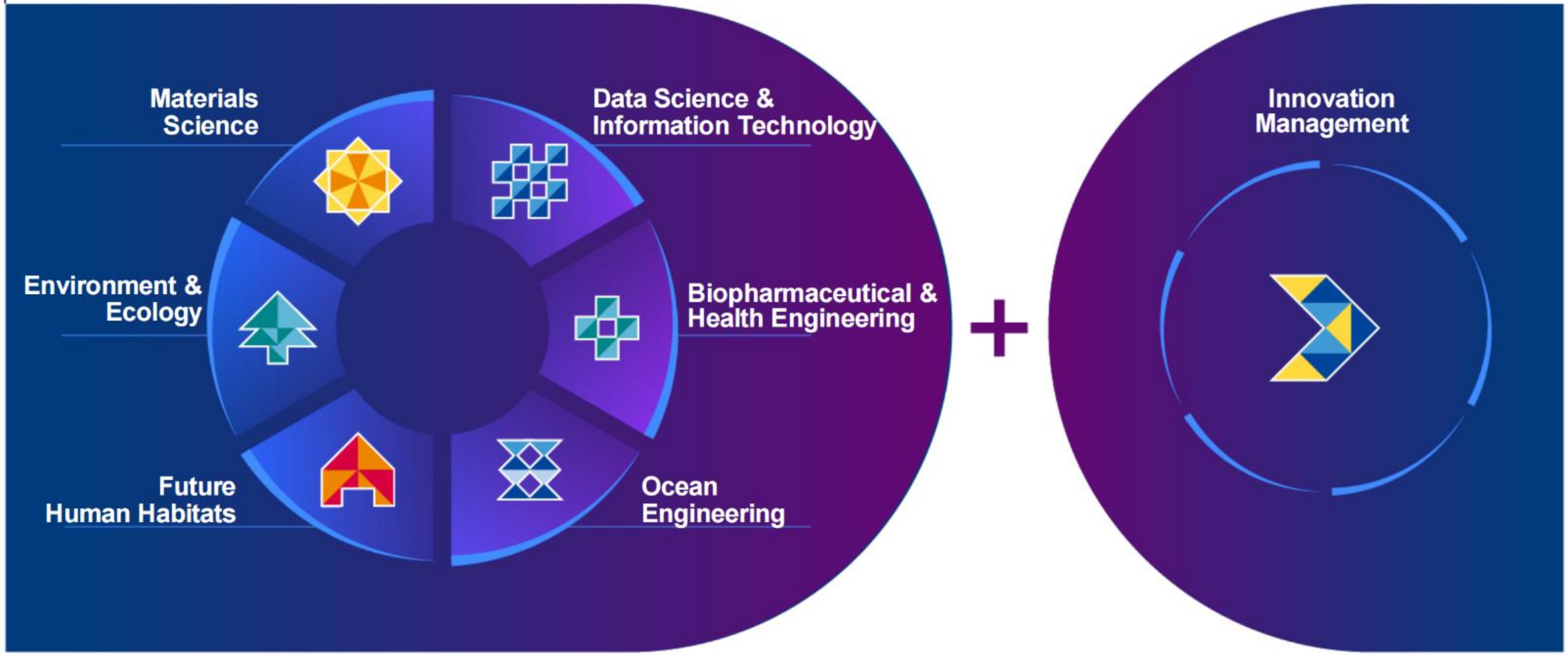
Master's students	4,490
Graduates	14,700+
Countries and regions represented by students	27
National Quality Courses	6
National & provincial/ministerial laboratories	23
Campus Area	22 hectares
Doctoral students	1,366
Full-time faculty members	230
Provincial/ministerial-level awards	70
Tsinghua University Quality Courses	15
Patents published	5,100+

* May 2025

Academics

Academic Disciplines

SIGS prioritizes the development of first-class engineering disciplines at Tsinghua University, complemented by the Innovation Management discipline. These key disciplines align closely with the industry development needs of Shenzhen, advance the city's industry transformation, and support the innovation and development of the Guangdong-Hong Kong-Macao Greater Bay Area. These disciplines support Tsinghua′s vision to become a leading global university.

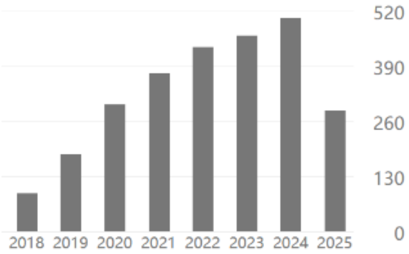


About Me

Shen Xinwei
Assoc. Professor
Tsinghua SIGS

Cited by VIEW ALL

	All	Since 2020
Citations	2756	2371
h-index	29	26
i10-index	51	48



期刊	学科排名
电力系统自动化	前1% (15/7951)
电力系统自动化	前1% (217/68906)
电力自动化设备	前1% (226/68906)

●**Education/Working Experience:**

□2006.09-2016.01 B. Eng. /Ph. D. in Tsinghua Univ.

✓ 2014, ECE at IIT, Visiting Scholar

□2016-2021 TBSI Postdoc/Research Scientist

✓ 2017, UCB/ 2021, University of Macau, Visiting Scholar

●**Research topics: Power system/integrated energy system optimization**

□ GS Cited 2700+, H-index 29

□ Top 1% Highly-cited Scholar in CNKI of 2024

□ 8 Chinese journals “High Impact” article

□ PI in several NSFC/Guangdong Research Projects

□ Excellent Youth Basic Research Fund of Shenzhen (深圳市优青)

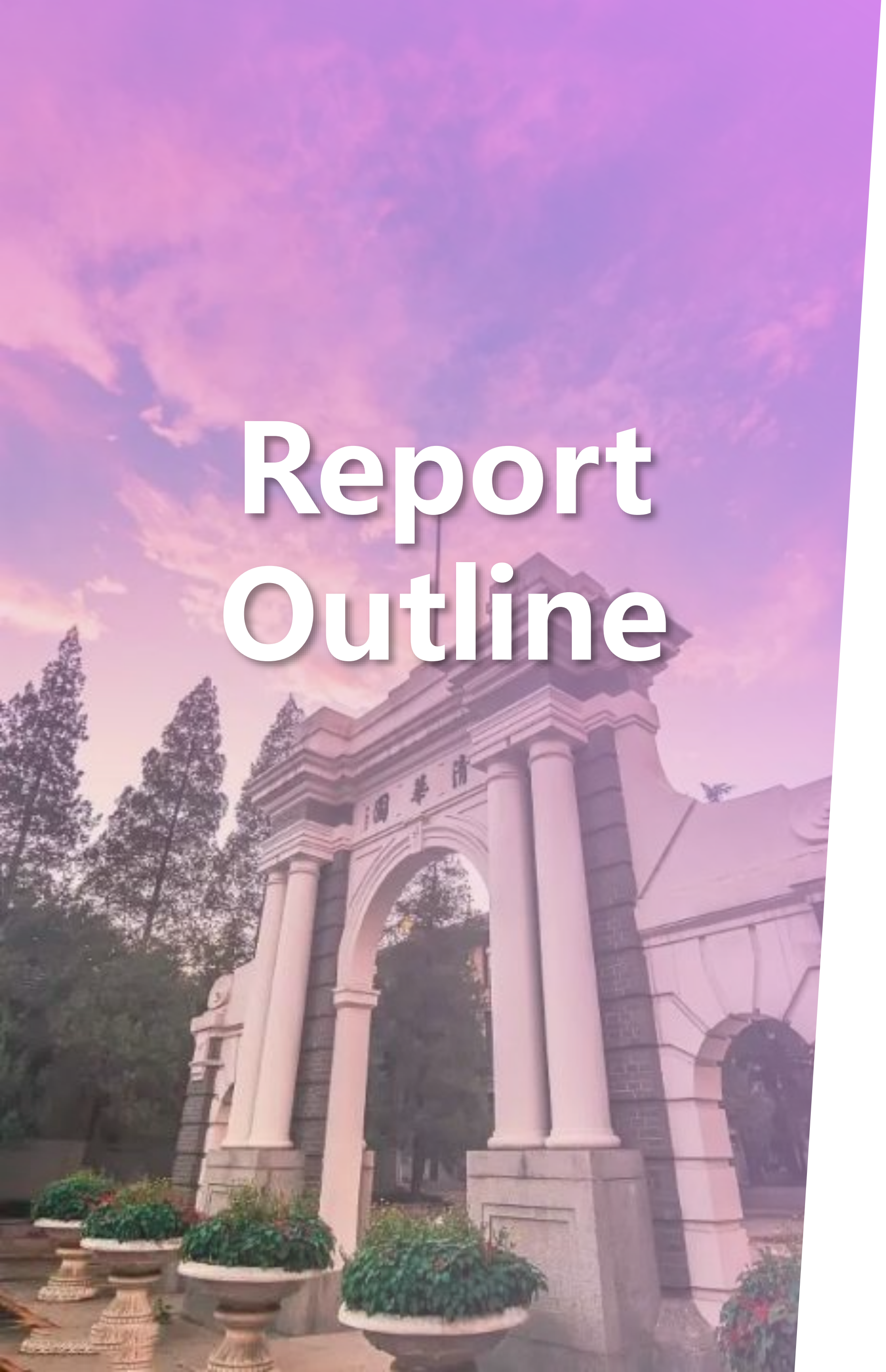
About Me

●Academic Services:

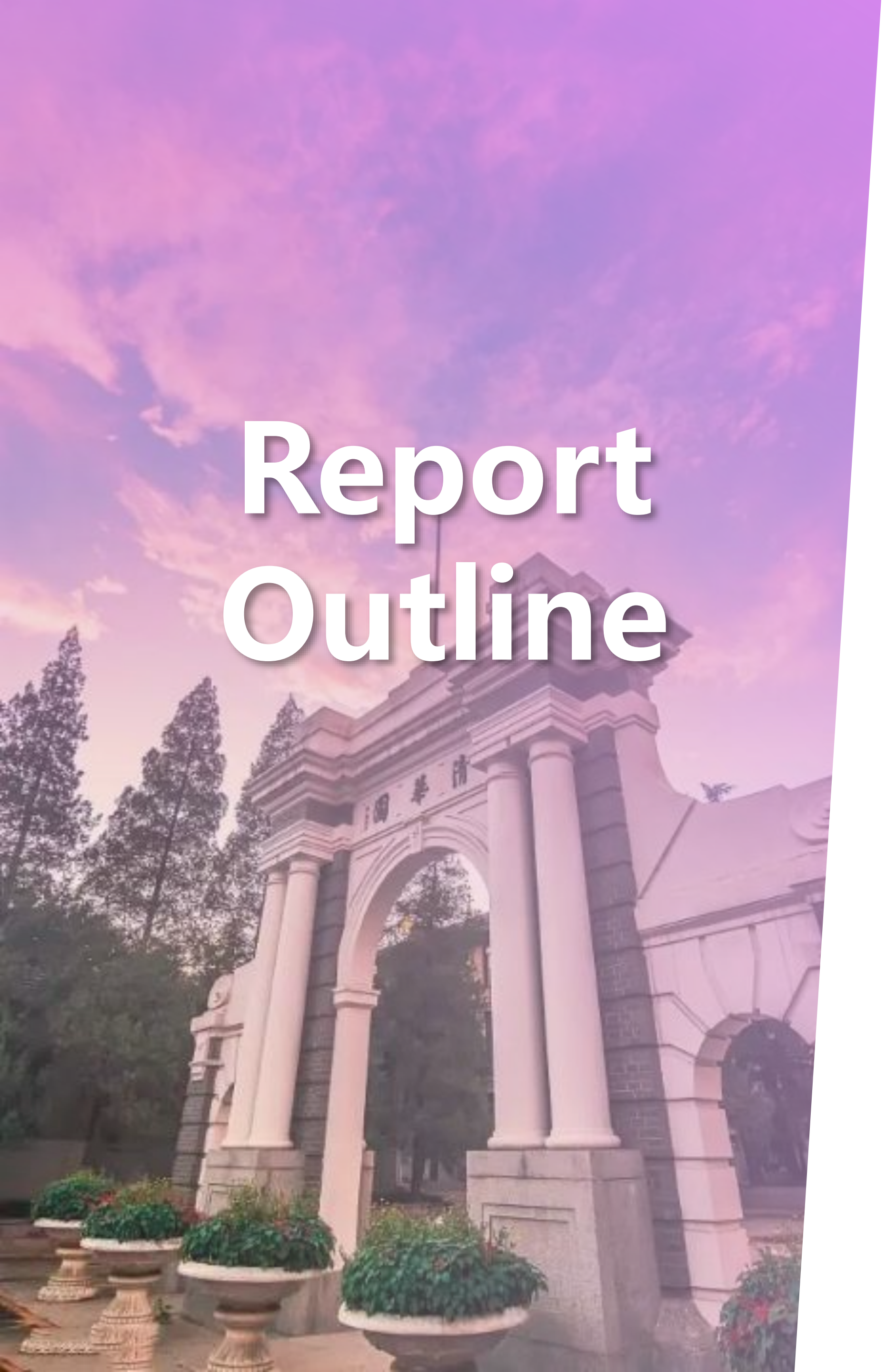
- ☐IEEE Senior Member/CSEE Member/CES Senior Member
- ☐IEEE Energy Internet Coordinating Committee (EICC) secretary
- ☐CSEE JPES(Q1)/Applied Energy(Q1) Young Editor

● Selected Honors:

- ☐ **IEEE PES Tech. Council Young Professional Award (2023, first recipient in Asia Pacific Region)**
- ☐ 2023 CSG S&T Award/ Guangdong Electric Power S&T Award
- ☐ 2020 CSEE "Youth Talent Support Project"
- ☐ "F5000"China's Excellent S&T Paper/ CSEE Outstanding Paper



Report Outline



Report Outline

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

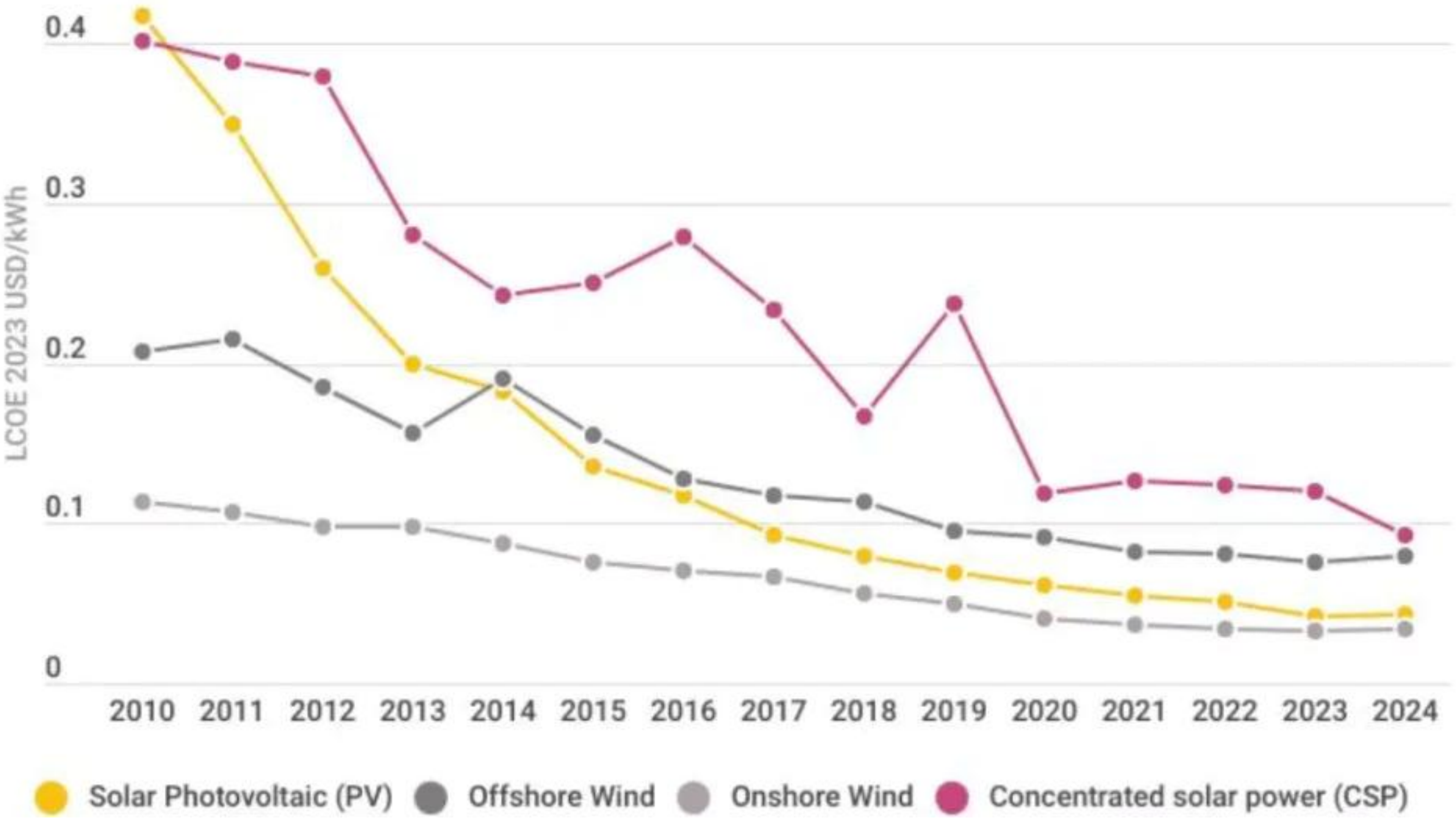
- **8~14MW** offshore wind turbines have been applied.
- **16+ MW** have also been released.
- **Over 1 Trillion USD** will flow into the global offshore wind industry before 2035.

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!

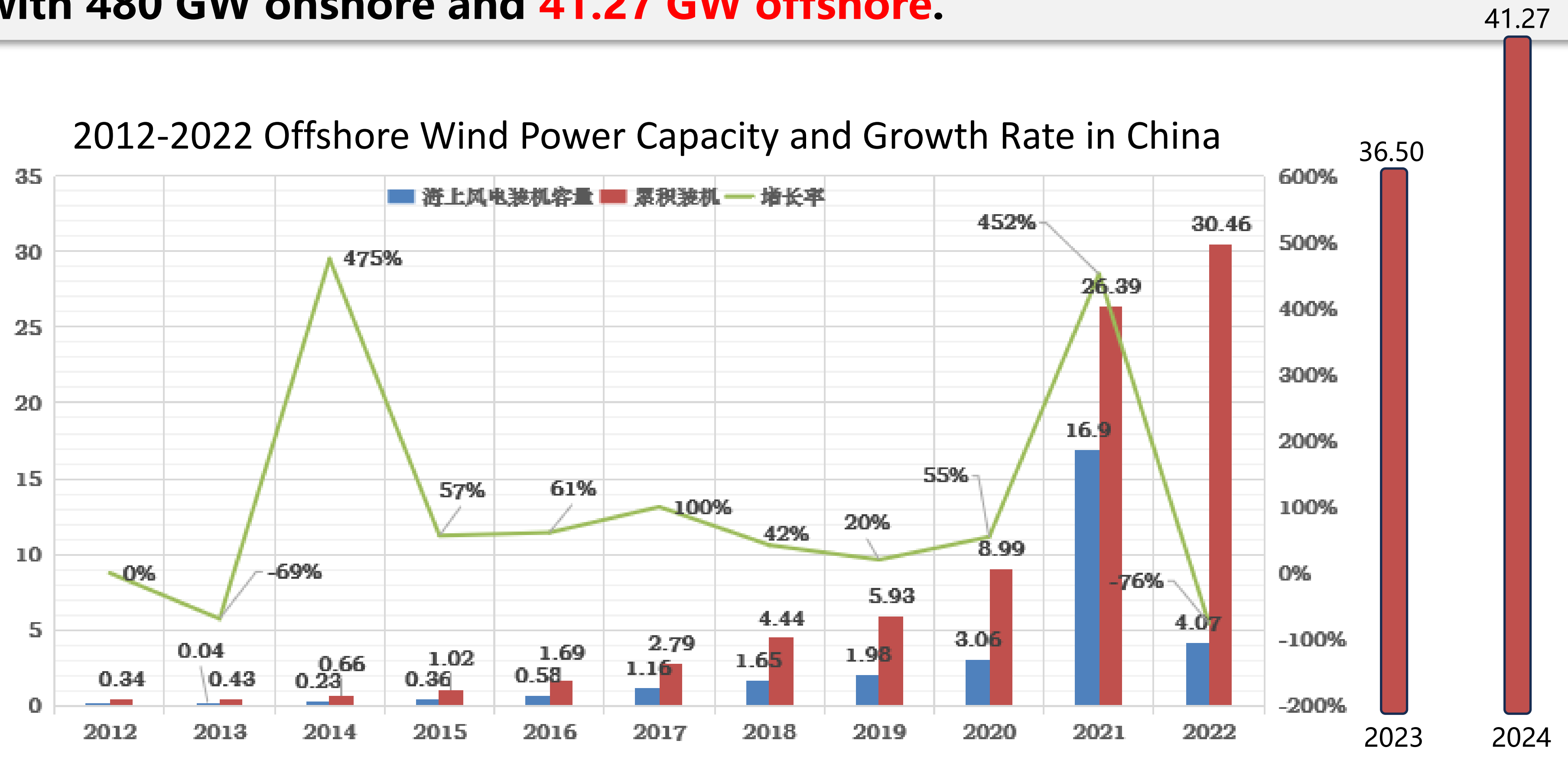
- **Significant efforts have been made to drive cost reduction, enhance performance, and accelerate the large-scale deployment of offshore wind power worldwide.**
- **"The cost-competitiveness of renewables is today' s reality…the avoided fossil fuel costs in 2024 reached up to $ 467 Bn. "**——Francesco 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.



Ship carrying Hydrogen

"COSCO SHIPPING YANGPU" (2025)
First Ship using Methanol as fuel in China

"Hydrogen"

- H_2
- Methane
- Methanol
- Ammonia

● Black Hydrogen

Produced from coal

● Grey Hydrogen

Produced from Oil and Gas

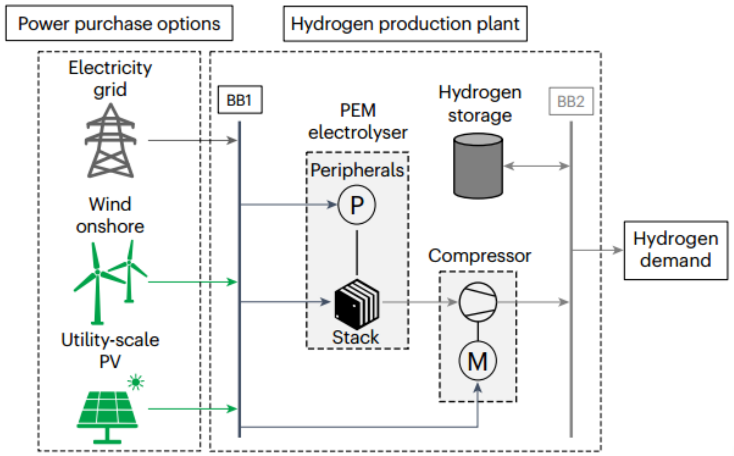
● Blue Hydrogen

From Oil and Gas but with CCUS

● Green Hydrogen

Produced From renewable energy

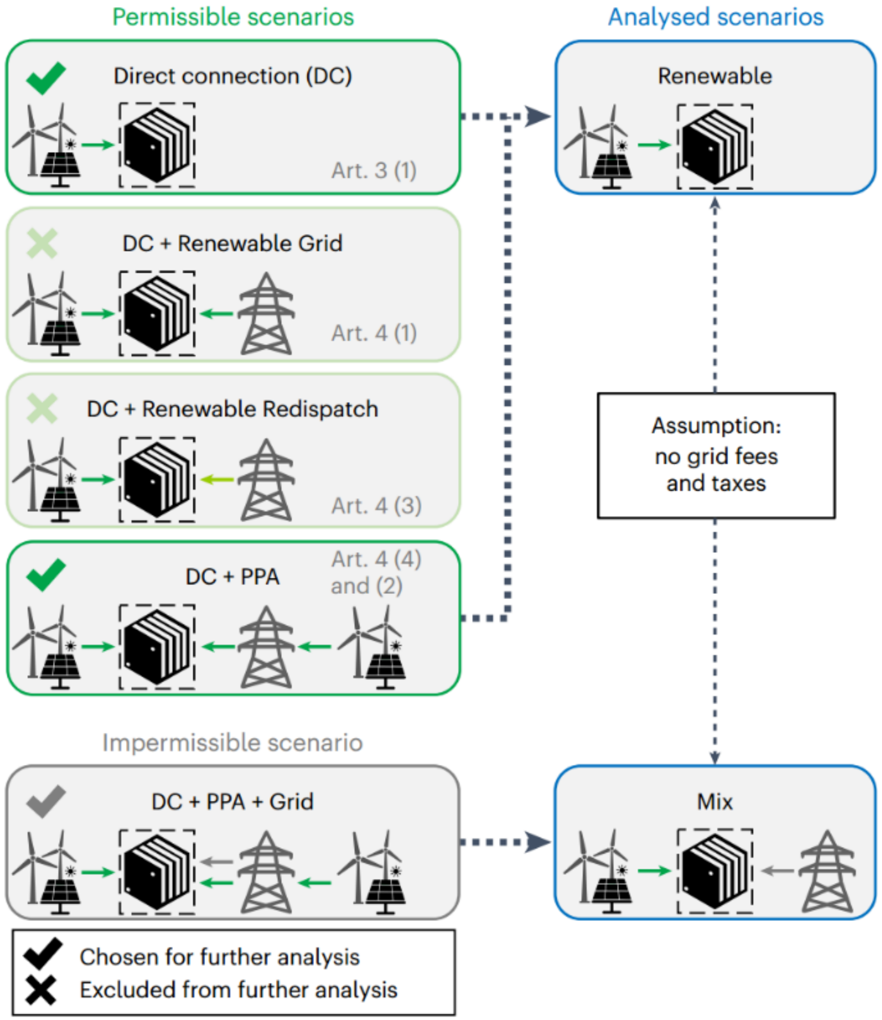
EU Regulations define "green", which affects production system configuration significantly[1]



system configuration

"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 <= the renewable power.

$$\sum_{t=k\times730+1}^{(k+1)\times730}(P_{\mathrm{ElySys},t}) - \sum_{t=k\times730+1}^{(k+1)\times730}(P_{\mathrm{nom,WT}}\times p_{\mathrm{WT},t}+P_{\mathrm{nom,PV}}\times p_{\mathrm{PV},t}) \le 0 \qquad \forall k\in\{0,1,2,\ldots,11\}$$

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

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

- Carbon Emission Intensity Calculation/Limitation

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

[1] Brandt J, et al. Cost and competitiveness of green hydrogen and the effects of the European Union regulatory framework. in Nature Energy, 2024.

Background ❯❯ Urgent Need for Maritime Decarbonization

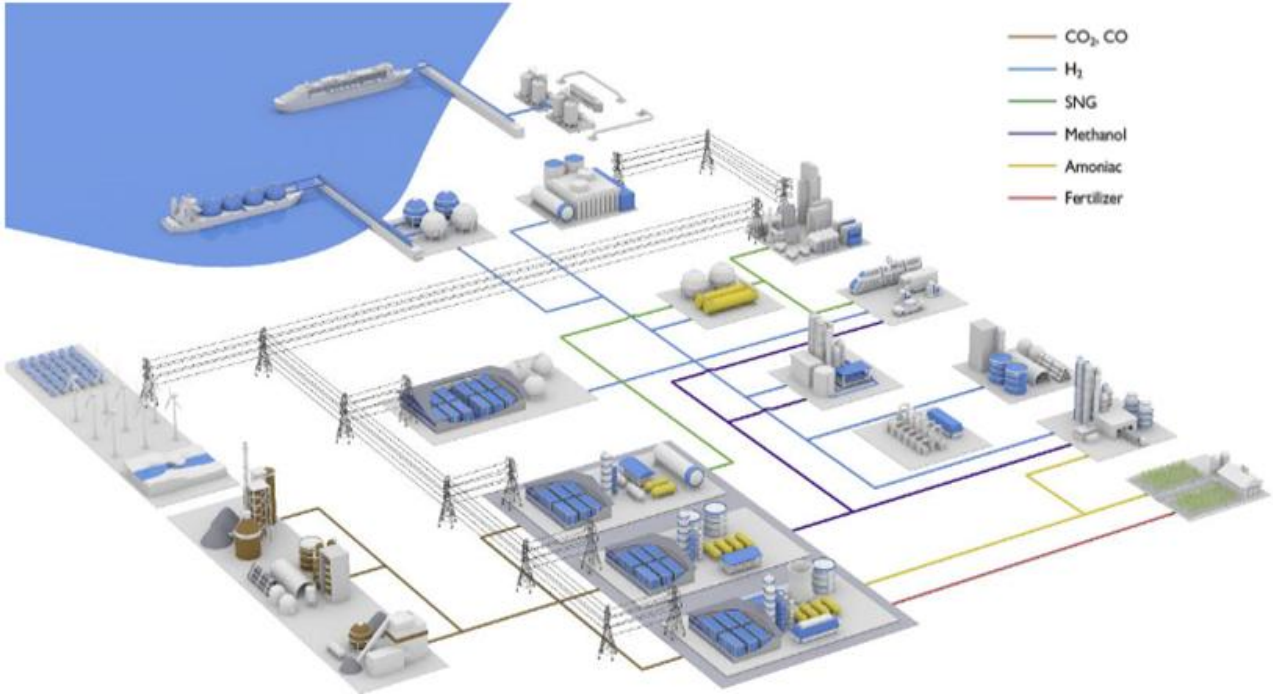
- ◻ **IMO MEPC 80**: Cut annual greenhouse gas (GHG) emissions from international shipping by at least 20%, with an ambition to reach 30%, by 2030 compared to 2008.
- ◻ **USA**: Clean Shipping Act
- ◻ **EU**: EU Emission Trading System（ETS）[1]、FuelEU Maritime Regulation[2]

- **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.

[1]Directive (EU) 2023/959 [2]Regulation (EU) 2023/1805

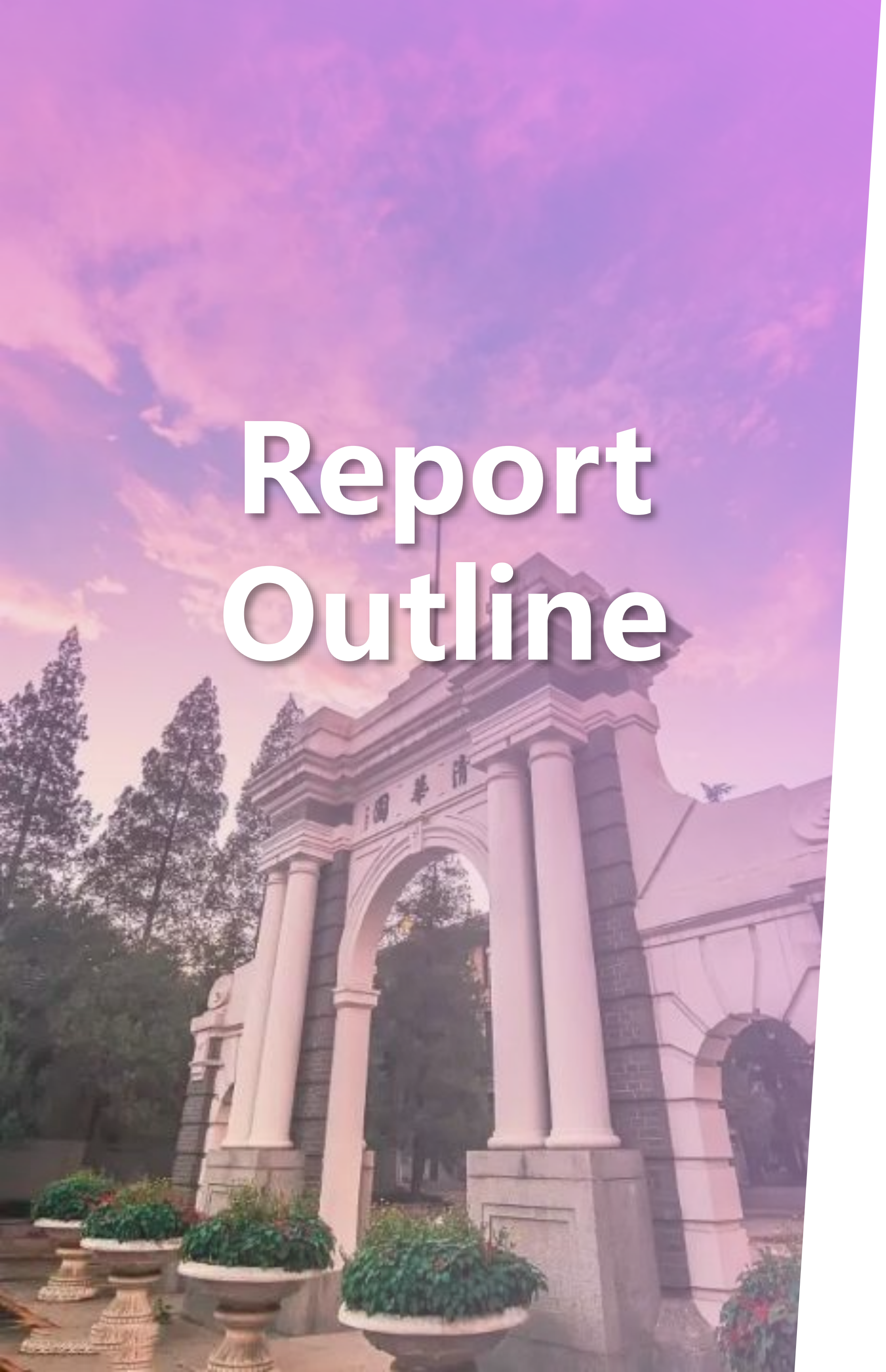
- In the first half of 2024, alternative fuel-powered ships accounted for 41% of the new ship orders globally
- Main alternative, the renewable fuels of non-biological origin (RFNBO), are green hydrogen
- With carbon policies, shipping companies are willing to pay for the transition to RFNBO



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

Overall Framework

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

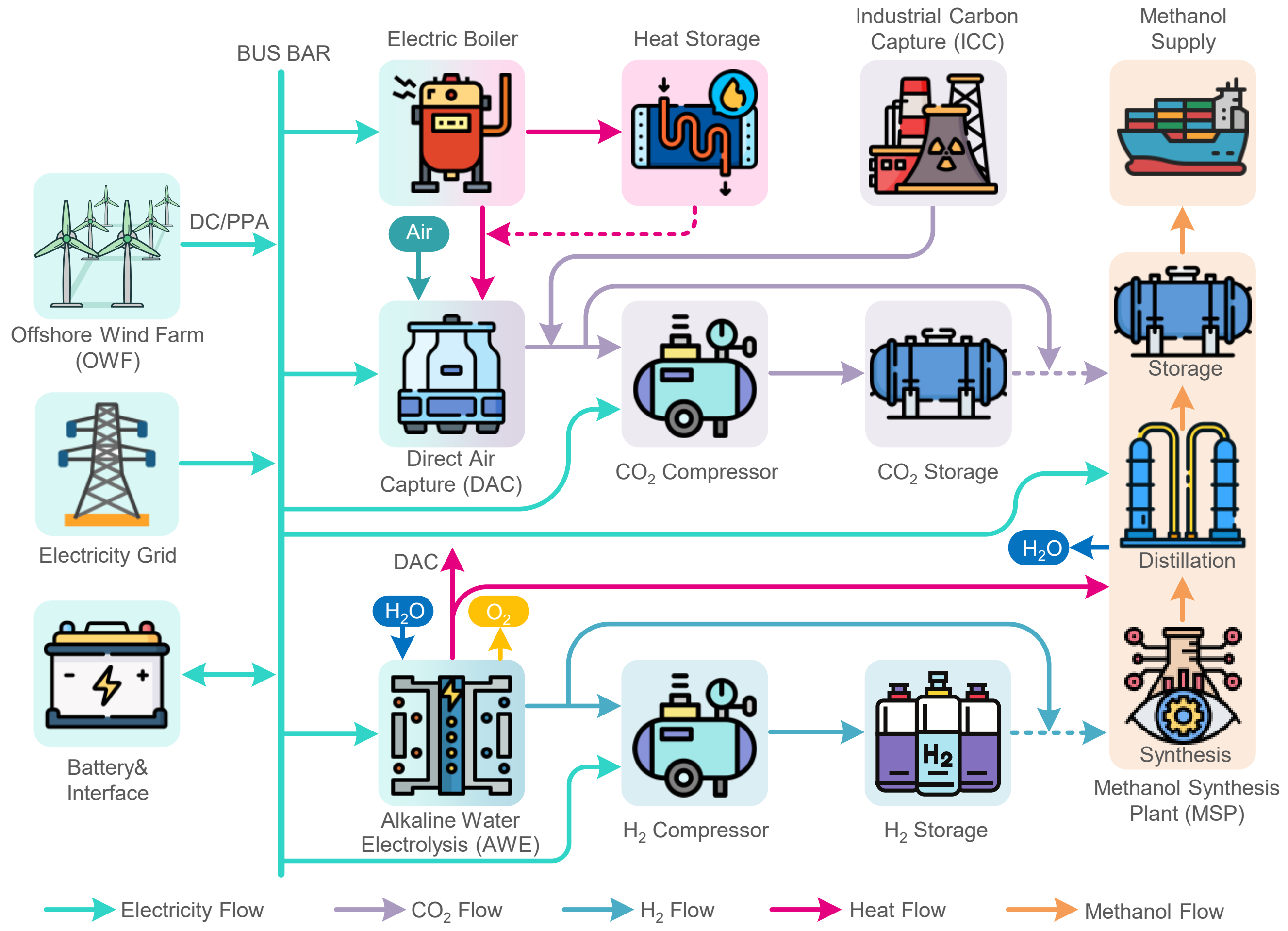
- Generate system configuration scenarios with different electricity and carbon sources
- Introduce evaluation indicators to assist scenario decision-making

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



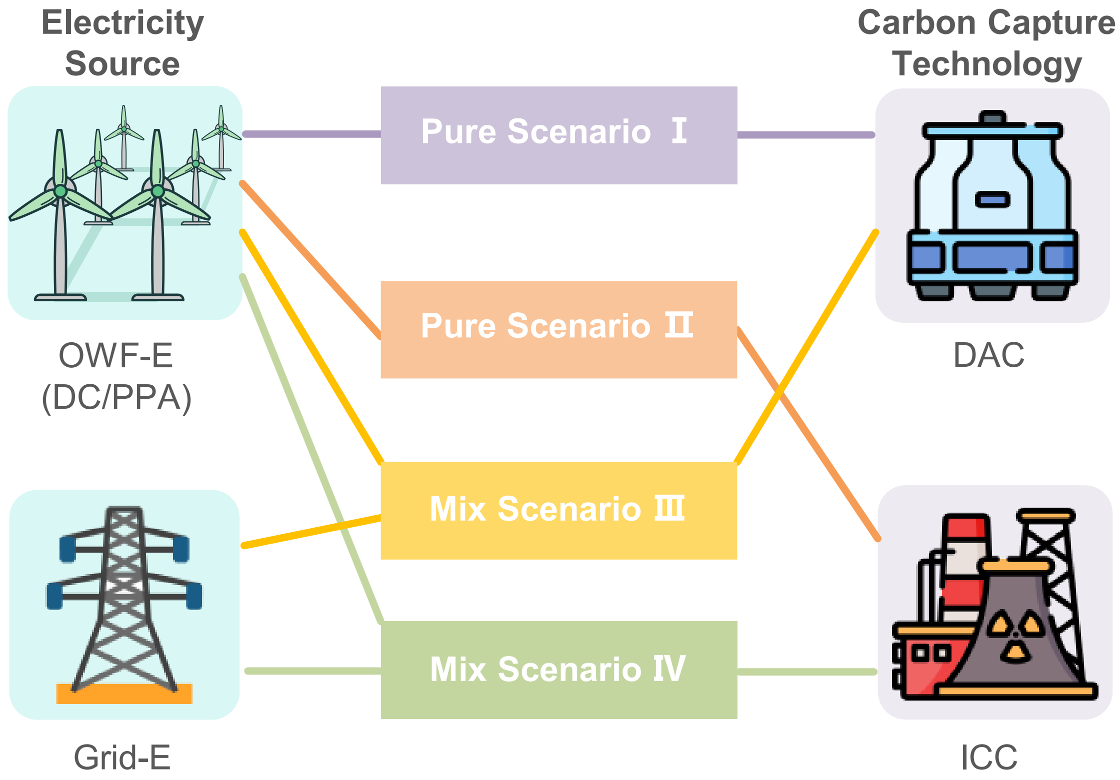
- ✓ **Electricity**: OWF, electricity grid, battery energy storage
- ✓ **Gas**: Methanol synthesis system (MSP), alkaline water electrolysis (AWE), hydrogen compressor and storage
- ✓ **Heat**: Waste heat from electrolysis, electric boilers, heat storage
- ✓ **Carbon**: Direct air capture（DAC）, Industrial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

[1]Commission Delegated Regulation (EU) 2023/1185 [2]Commission Delegated Regulation (EU) 2023/1184 [3] Directive (EU) 2018/2001

Scenario & Indicator design

□ 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...

Mathematical Optimization Model

Input and output characteristic of devices

Energy balance

$$EF^{EX}_{h,k} + \sum_{n=1}^{N} EF^{OUT}_{n,h,k} = \sum_{n=1}^{N} EF^{IN}_{n,h,k}, \quad \forall h,k$$

Energy conversion

$$EF^{OUT}_{n,h,k} = \lambda_{n,k',k} \times EF^{IN}_{n,h,k'}, \quad \forall n,h,k,k'$$

Working scope

$$CAP_{n,k} \geq 0, \quad \forall n,k$$

$$\xi^{MIN}_{n,k} CAP_{n,k} \leq EF^{IN}_{n,h,k} \leq \xi^{MAX}_{n,k} CAP_{n,k}, \quad \forall n,k$$

Ramping constraint

$$EF^{IN}_{n,h,k} - EF^{IN}_{n,h-1,k} \leq \mu^{UP}_{n,k} \times EF^{IN}_{n,h-1,k}, \quad \forall n,h,k$$

$$EF^{IN}_{n,h-1,k} - EF^{IN}_{n,h,k} \leq \mu^{DOWN}_{n,k} \times EF^{IN}_{n,h-1,k}, \quad \forall n,h,k$$

Models of various energy storage devices

$$\delta^{IN}_{n,h,k} + \delta^{OUT}_{n,h,k} = 1, \quad \delta^{IN}_{n,h,k}, \delta^{OUT}_{n,h,k} \in \{0,1\}$$

$$0 \leq EF^{IN}_{n,h,k} \leq \delta^{IN}_{n,h,k} \times \xi^{MAX}_{n,k} \times CAP_{n,k}$$

$$0 \leq EF^{OUT}_{n,h,k} \leq \delta^{OUT}_{n,h,k} \times \xi^{MAX}_{n,k} \times CAP_{n,k}$$

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

$$SOC_{n,h,k} = SOC_{n,h-1,k} + (\eta^{IN}_{n,k} \times EF^{IN}_{n,h,k} - \frac{EF^{OUT}_{n,h,k}}{\eta^{OUT}_{n,k}}) \times \Delta h$$

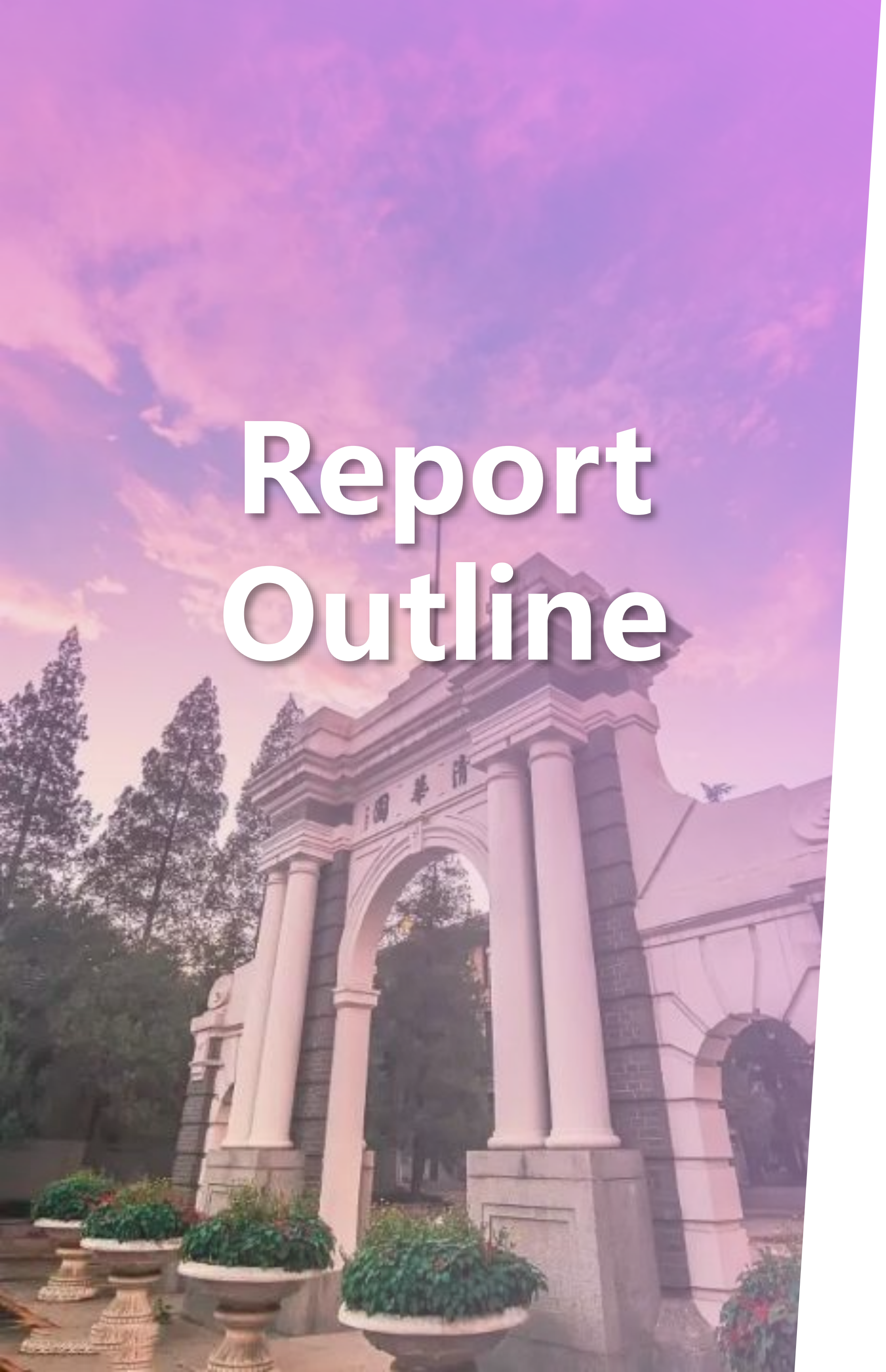
Objective function: Minimize LCOM

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

CAPEX: Capital Expenditure

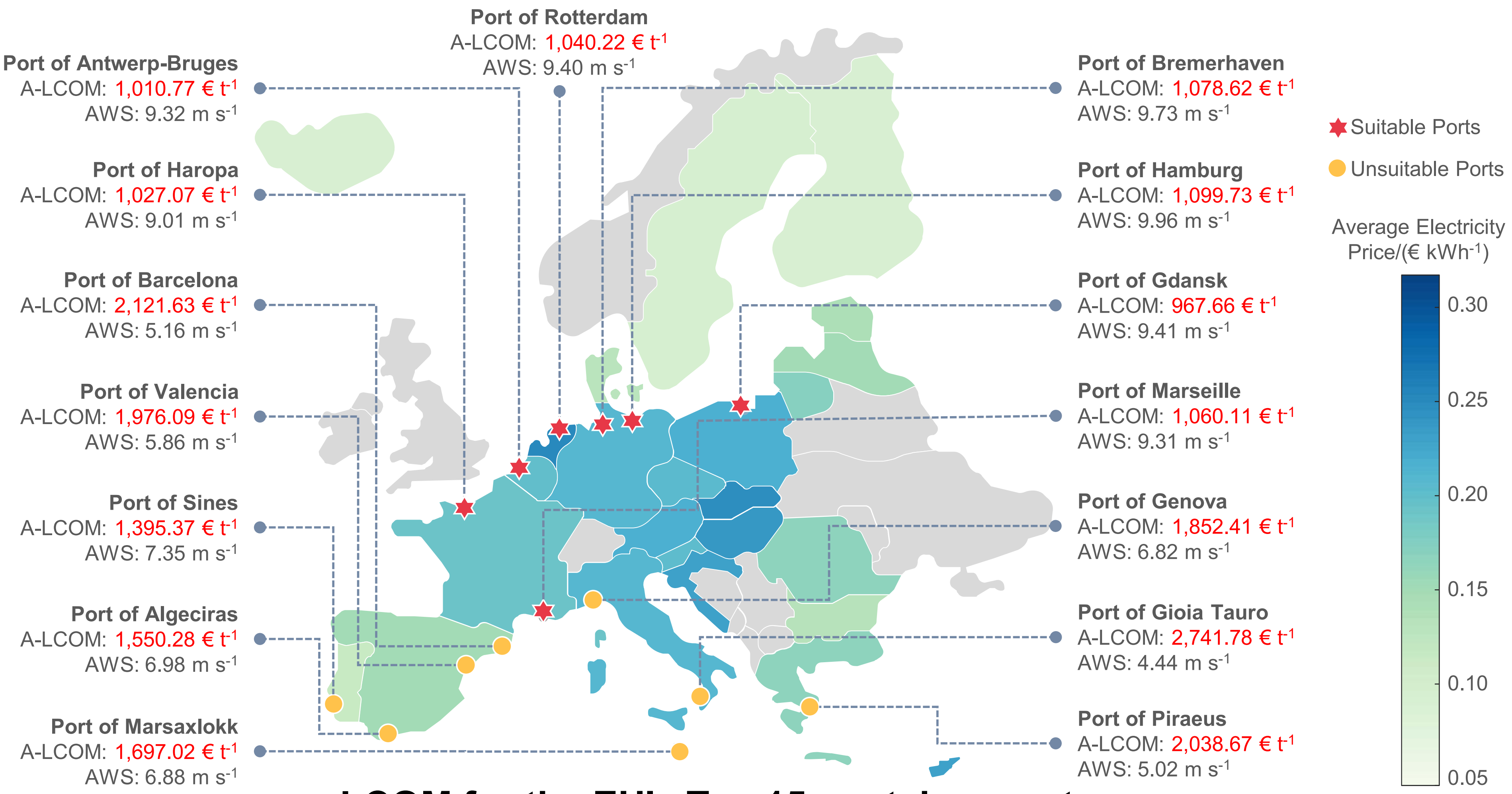
OPEX: O&M Expenses

EC: External costs



Report Outline

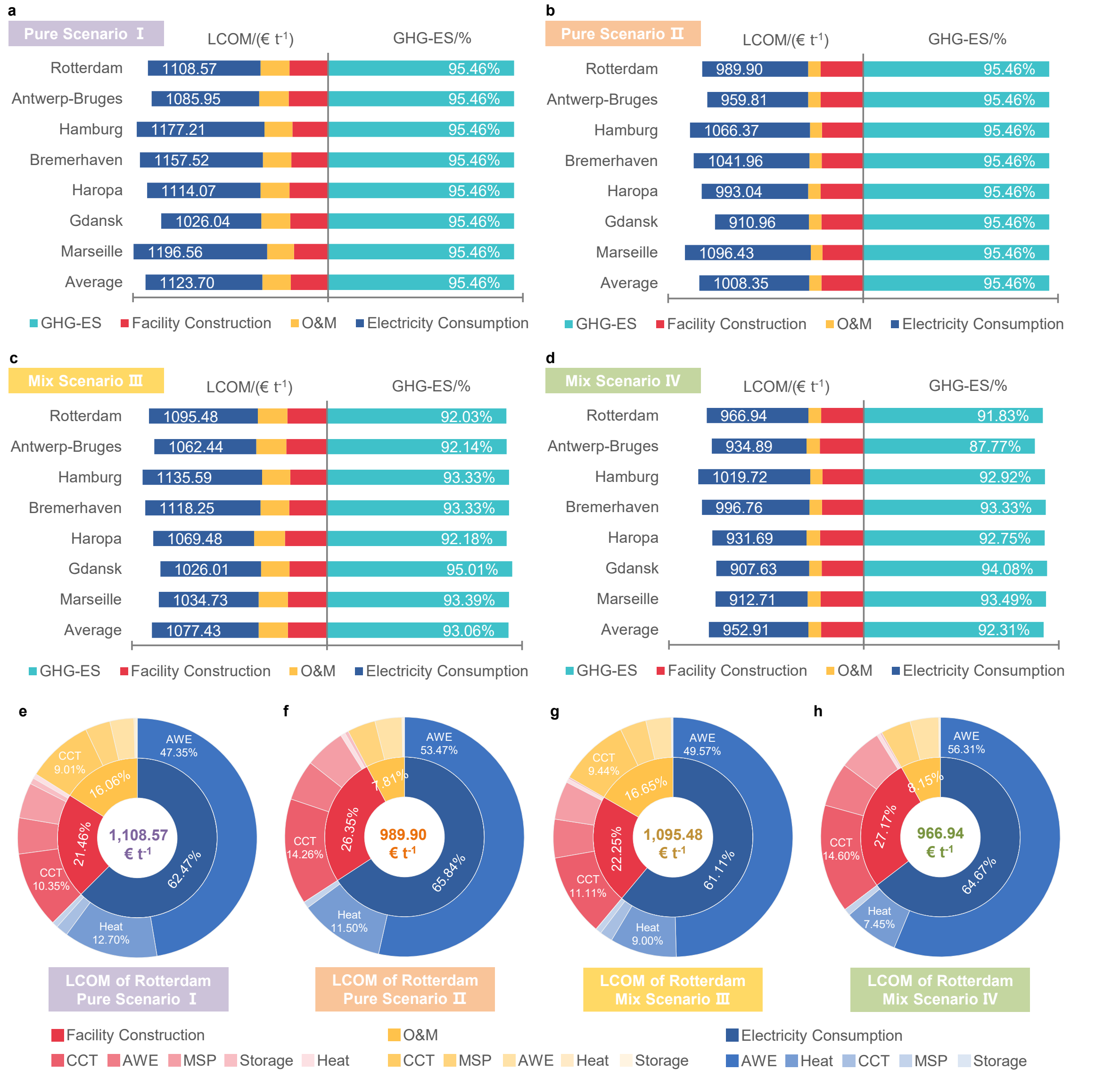
Production potential of green methanol in EU ports



LCOM for the EU's Top 15 container ports

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

Production potential of green methanol in EU ports



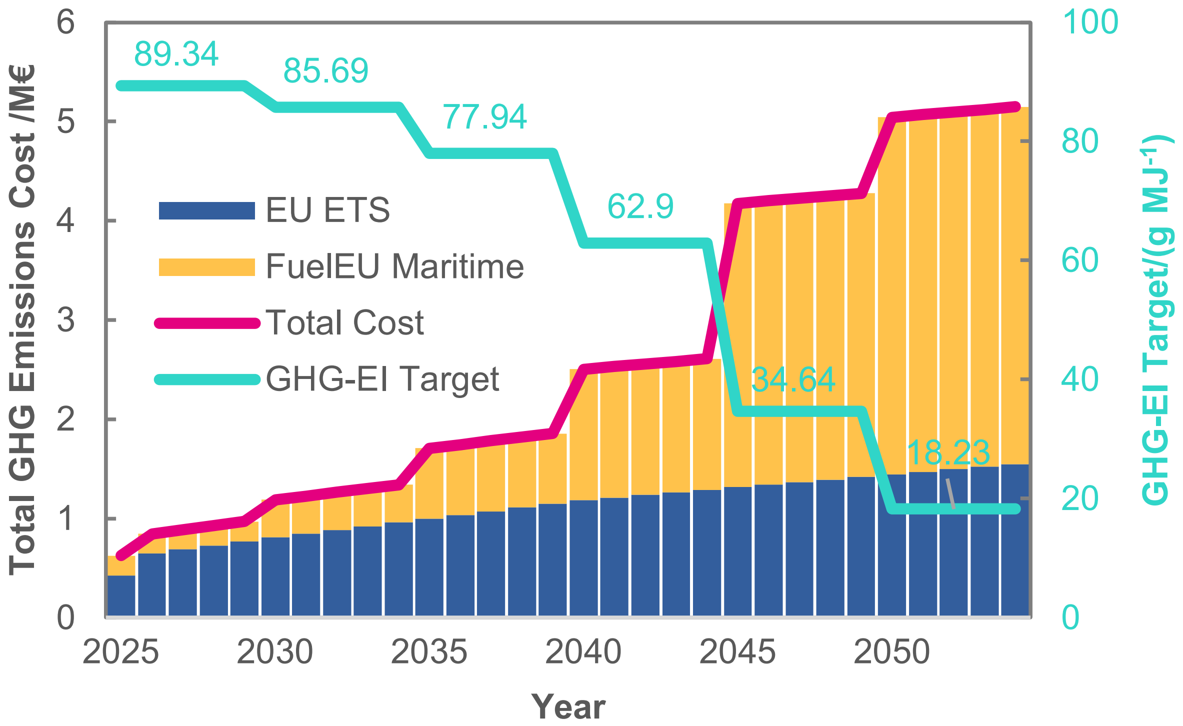
LCOM and GHG-ES for green methanol in selected 7 ports

In 2025:

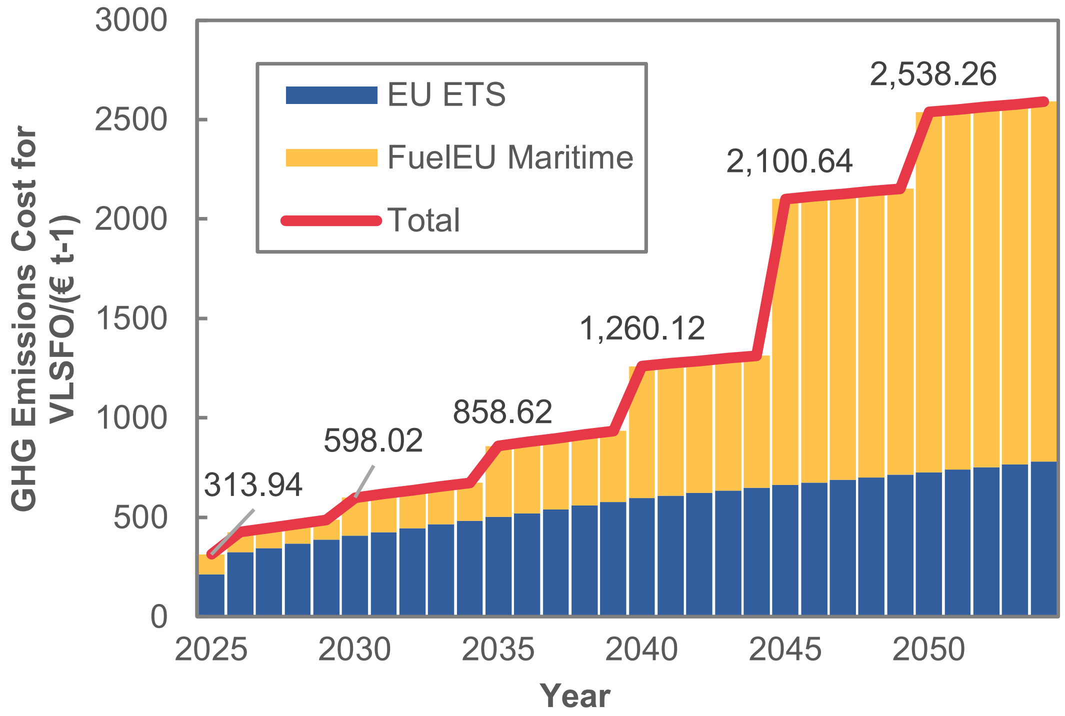
- LCOM is 907.63-1196.56 €/t, and electricity consumption accounts for >60%.
- The limited power supply of grid can smooth wind power thus reducing LCOM (Ⅲ< Ⅰ, Ⅳ<Ⅱ)
- Carbon source: ICC is more economical than DAC (Ⅱ< Ⅰ, Ⅳ<Ⅲ)

Conventional marine fuel cost forecast

Tsinghua Shenzhen International Graduate School



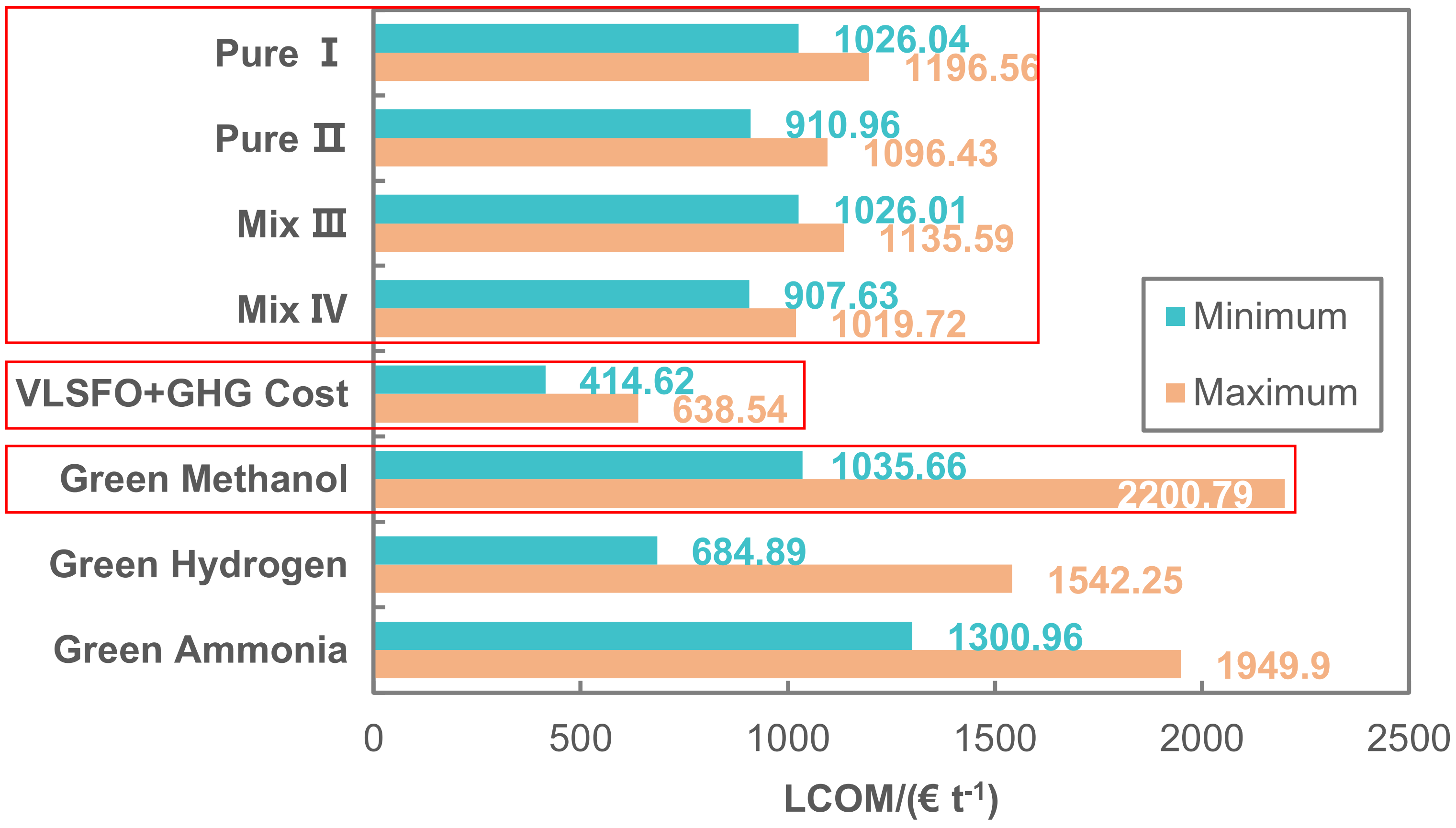
2025~2050 GHG costs for a large ship sailing within EEA



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



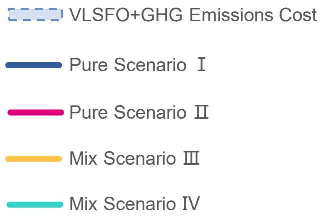
The equivalent LCOM of several potential solutions in 2025

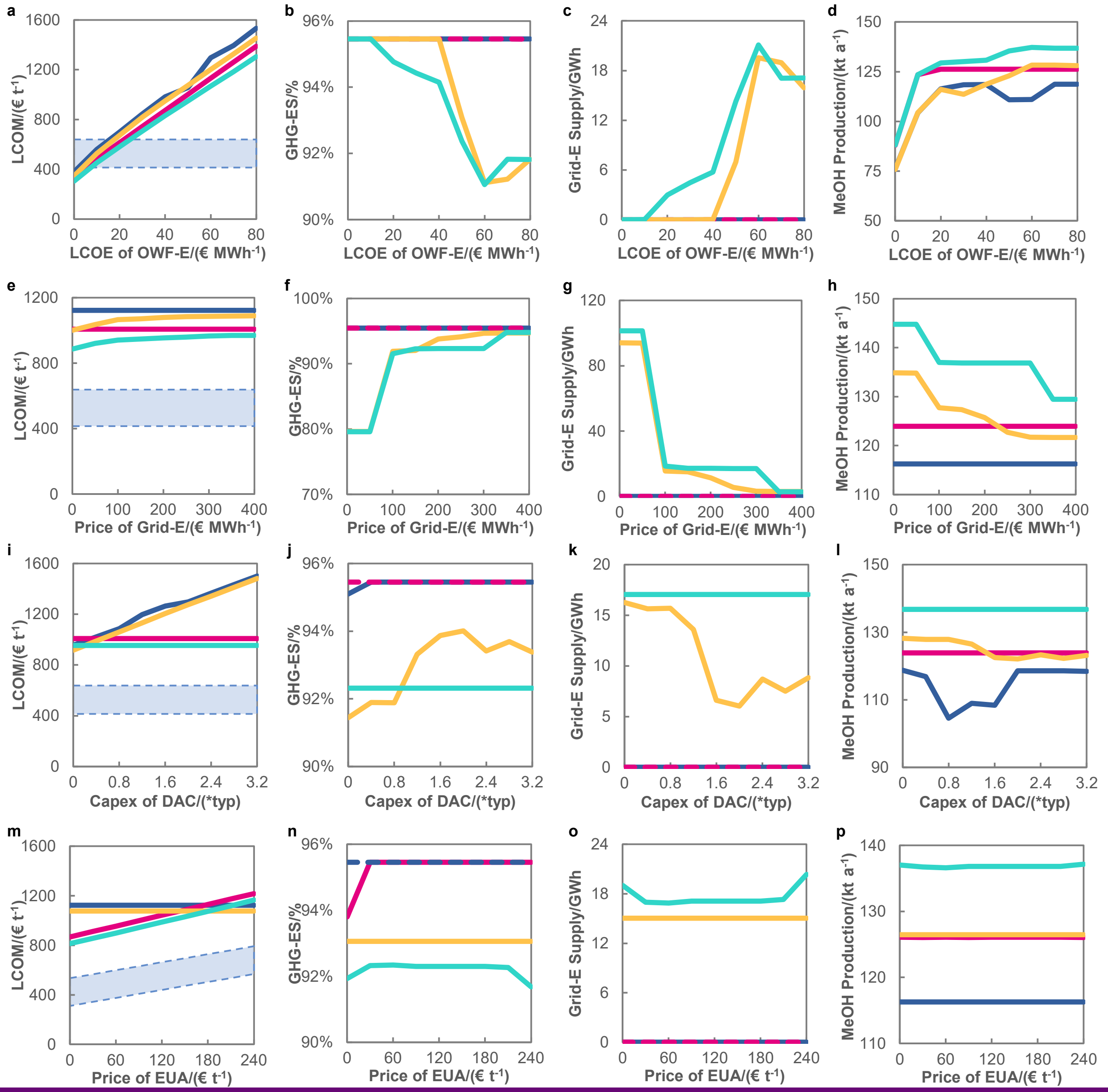
- LCOM of different scenarios is much lower than the that of most current green methanol projects (1035.66~2200.79€/t).
- The emission costs imposed on VLSFO are lower, with equivalent LCOM of 414.62~638.54 €/t.
- This may incentivize container ship operators to comply with regulations by paying fines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

Comparison between green methanol and VLSFO

☐ Sensitivity analysis of key factors

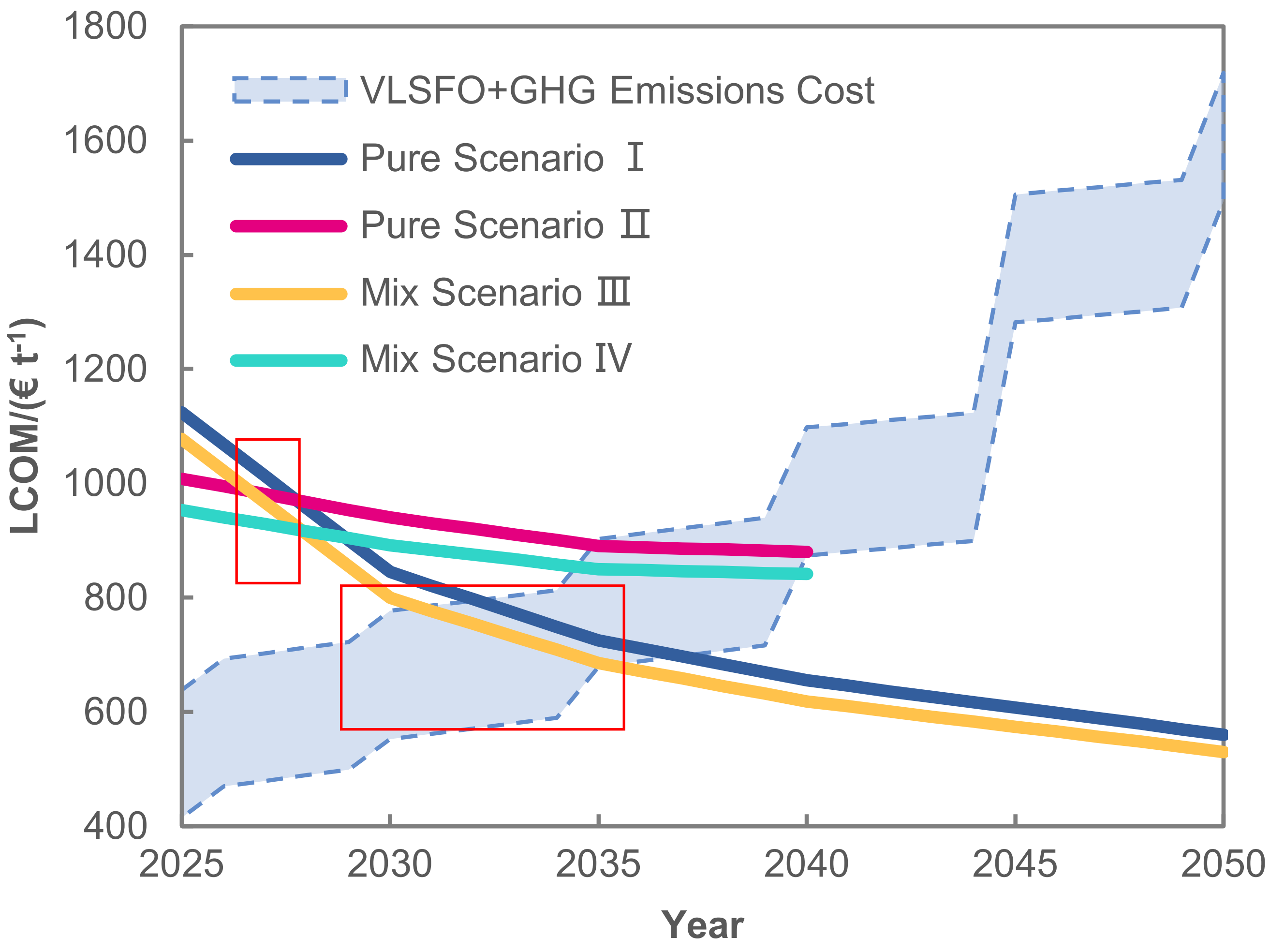
- wind power price
- electricity price
- DAC cost
- carbon price
- …





☐ 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)

Summary

Research Significance

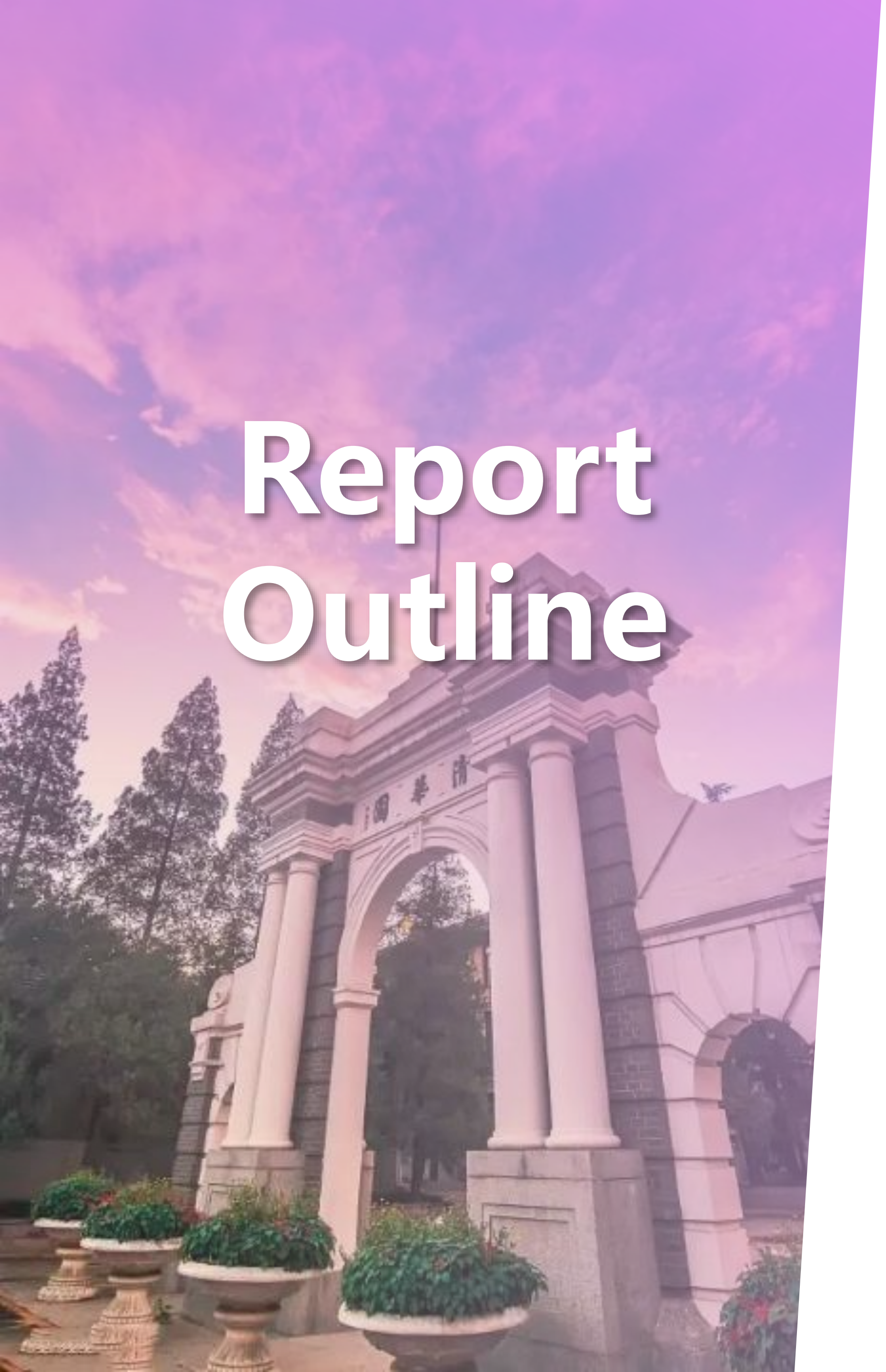
- As carbon policies continue to strengthen, shipping industry is looking for green fuels
- The economic benefits of green hydrogen are gradually emerging due to green premium

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

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

Wake effect among WTs
↓
Layout to reduce wake and increase power generation
↓
Wake effect
Strong non-convex

Long MTTR (reliability)
↓
Balancing economy and reliability
↓
Objective/constraint
complex

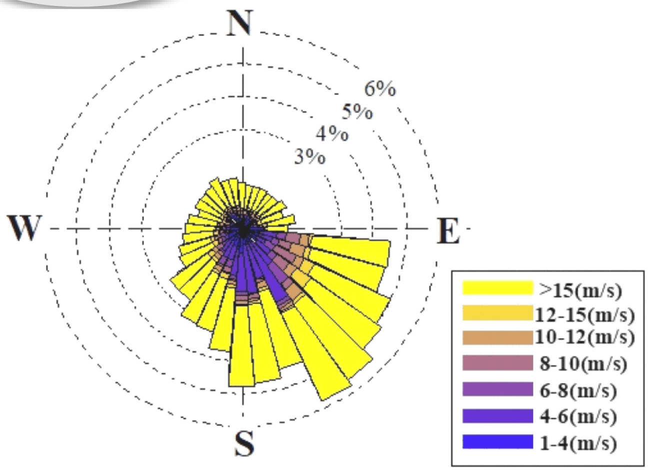
More products (economy)
↓
Reduce levelized cost of hydrogen (LCOH)
↓
Dynamic electrolysis characteristics

$$\min F(x)$$
$$\text{s.t. } G(x) \le 0$$
$$x \in D$$

Key Scientific Issues: Modeling and solving Complex Combinatorial Optimization problems

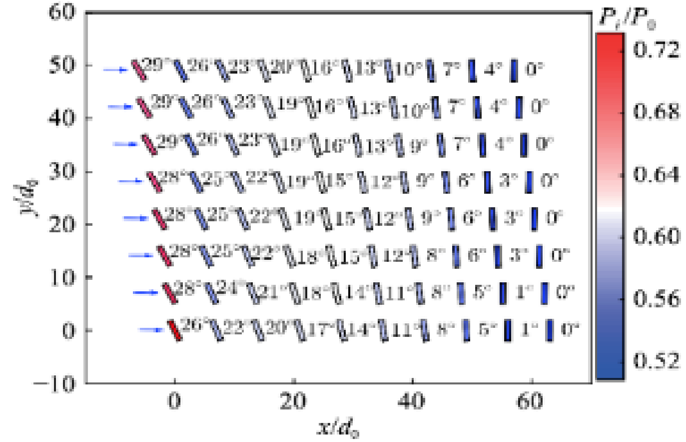
Key issue

Reducing wake effect by placing WTs in proper positions

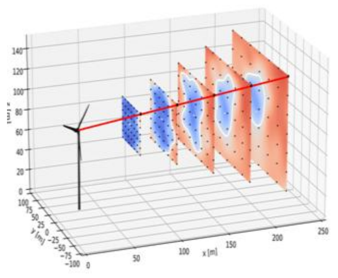


Wind Rose

Depicting multi wind scenes based on wind rose diagram

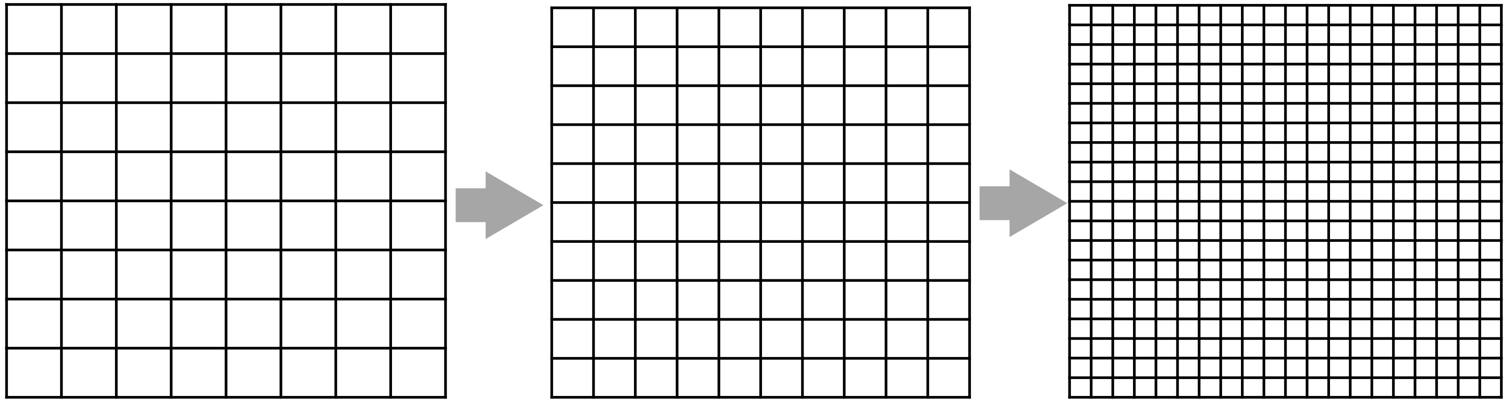


Wake quantification index



Facing the disaster of dimensionality as the scale increases

8×8 Grid | **10×10 Grid** | **20×20 Grid**



8×8 Grid	10×10 Grid	20×20 Grid
64 0-1variable	10 0-1variable	400 0-1variable
15120 Continuous variables	18000 Continuous variables	72000 Continuous variables
18144 Constraints	21600 Constraints	86400 Constraints

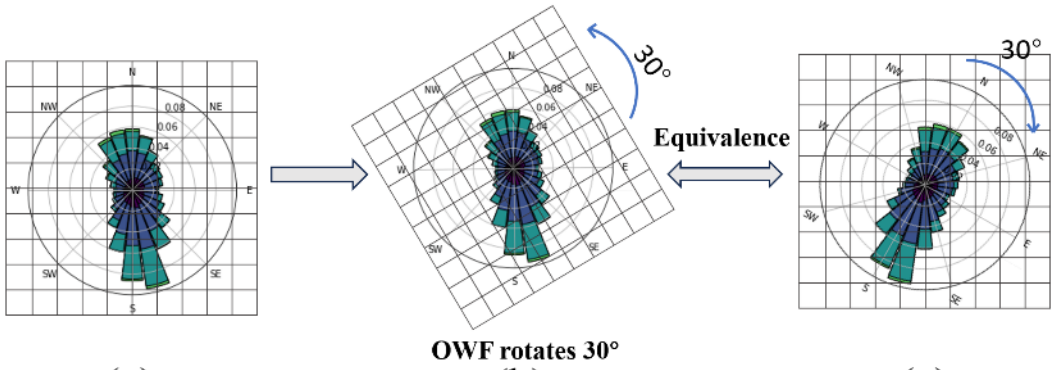
Ideas

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



(a) (b) (c)

Large-scale MIP-based model for initial solution

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

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

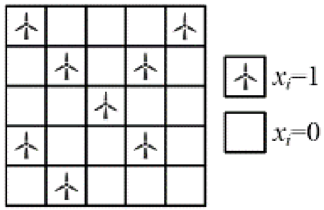
$$x_i + x_j \le 1 \quad \forall(i,j)\in$$

$$x_i + x_j - 1 \le y_{ij} \quad \forall i,$$

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

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

Initial layout plan

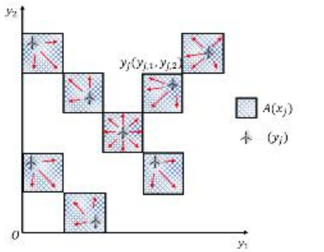


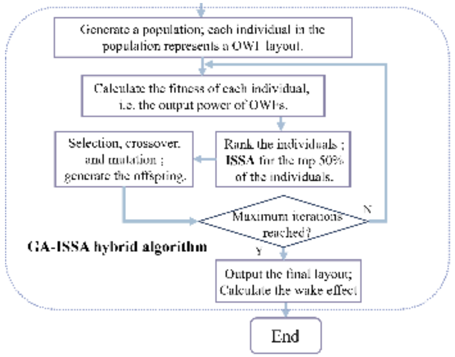
High-quality initial feasible solution

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 coordinate adjustment





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

➢ Two-stage optimization model for micro-sitting

1. Solve grid-based model by mathematical programming

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

Decision variables

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

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

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

WT output constraints

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

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

Sum of squared wakes from multiple WTs

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

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

Minimum safety distance constraint

2.Further optimization of WT coordinates

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

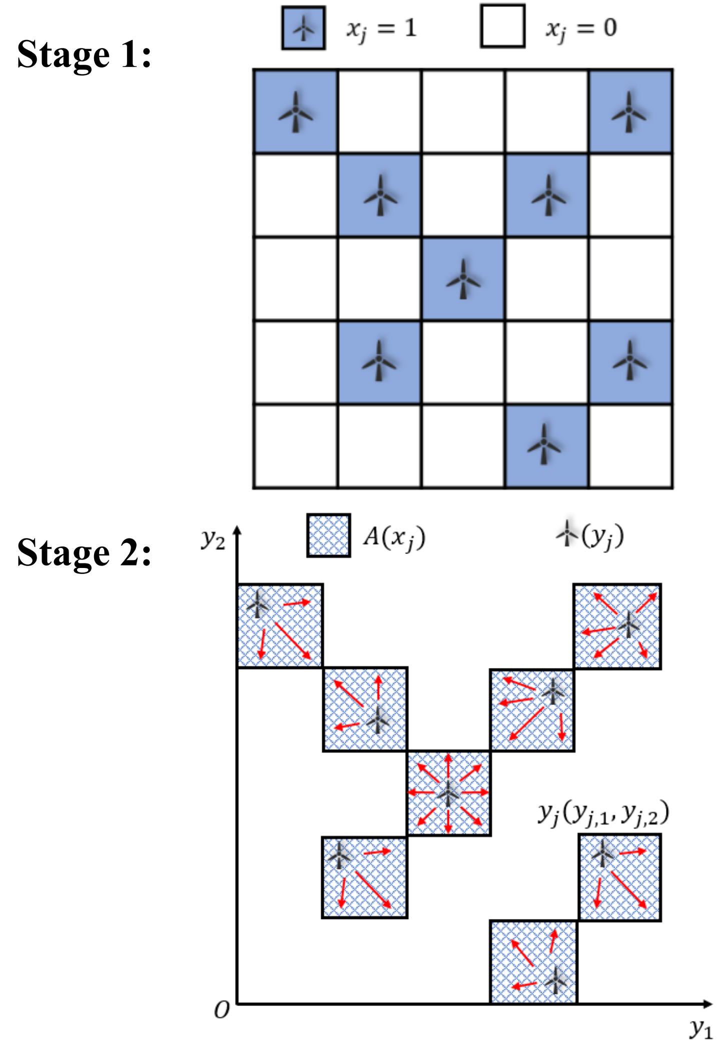
Decision variables: $y = (y_{j,1}, y_{j,2})$

$$\text{s.t.} \left(y_{j,1}, y_{j,2}\right) \in A(x_j)$$

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

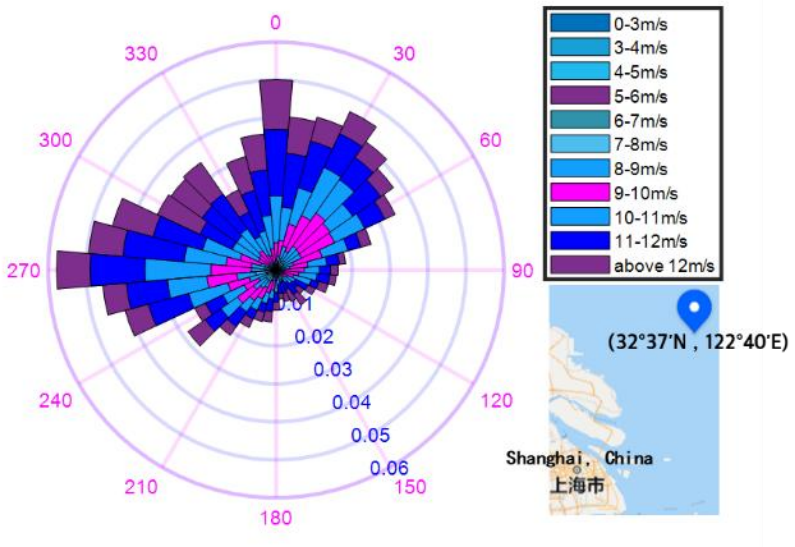
Minimum safety distance constraint

- Schematic diagram



➢ Two-stage optimization model for micro-sitting

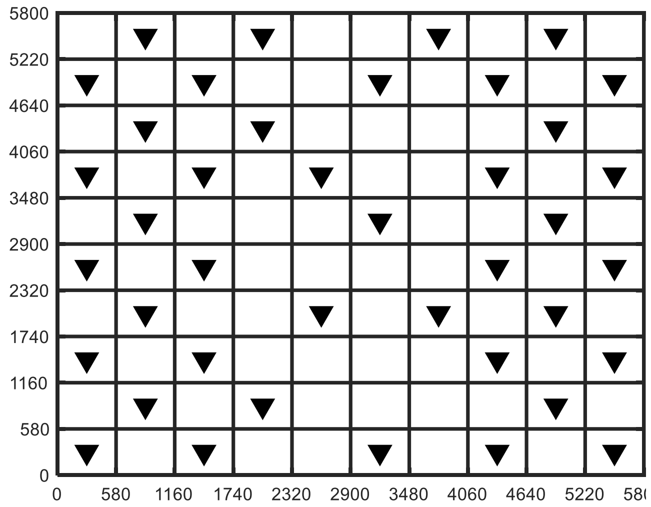
- **Case studies**



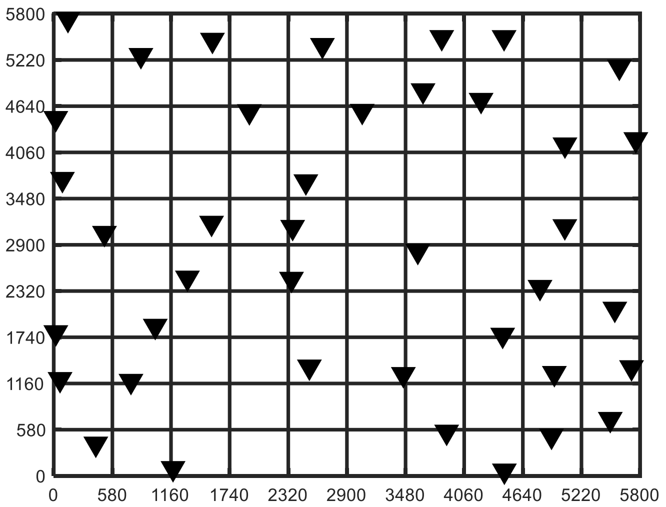
Jiangsu **200MW** OWF **micro-sitting**

- 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)

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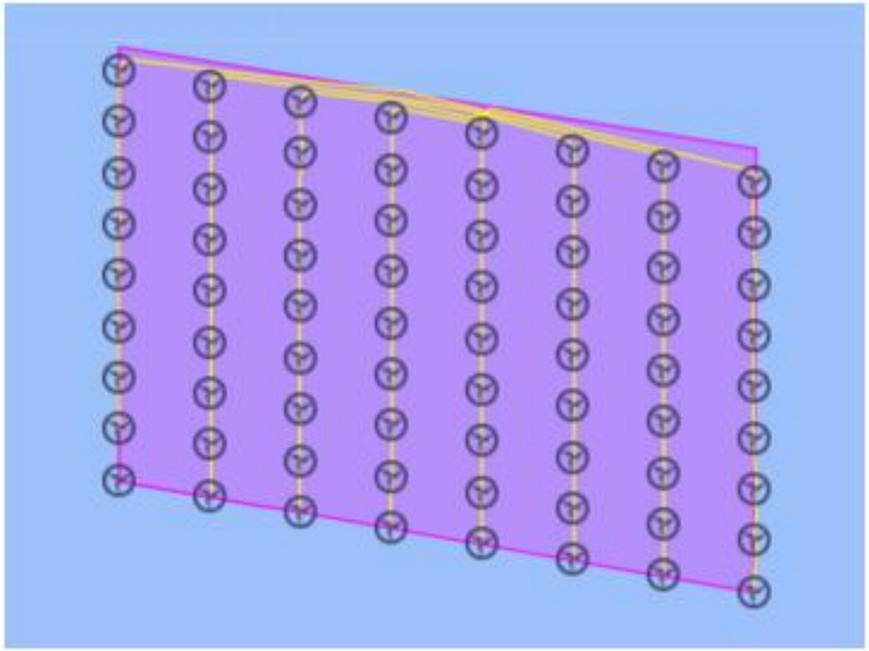
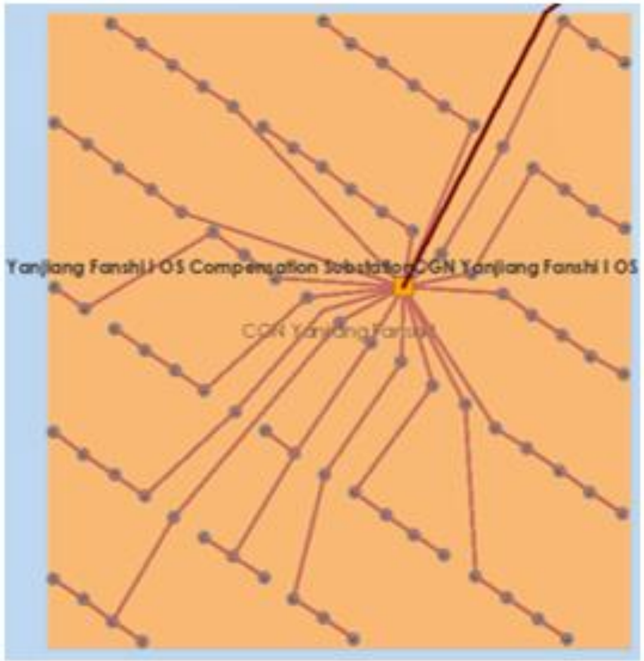
Key issue

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

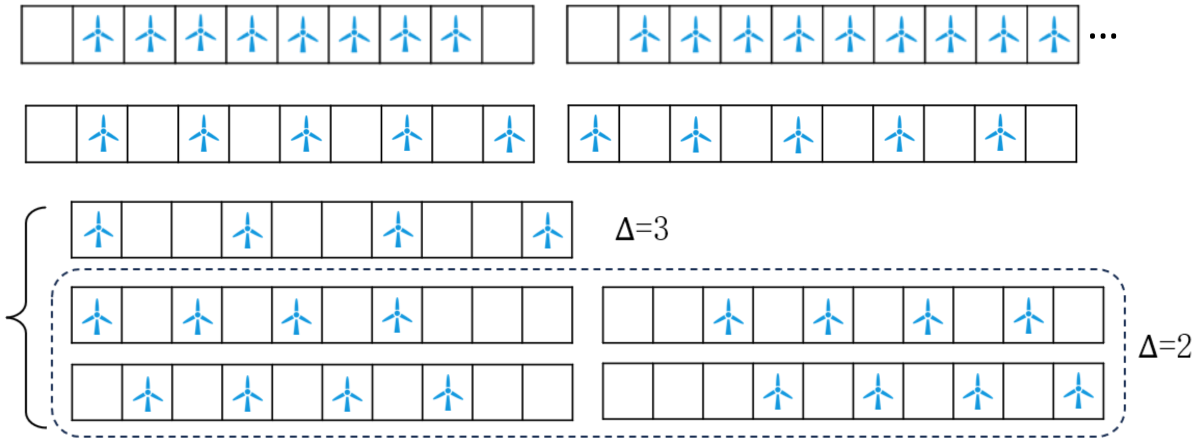
Micro-sitting model for WTs considering regular layout

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

Each row wts≥ 6

Each row WTs=5

Each row WTs=4



- **Phase 1 MILP Model**

$$\max \sum_{n\in N}\sum_{i\in I}\pi^n \hat{P}_i^n(x_i, v_i^n)$$

$$s.t. \sum_{i\in I} x_i = N$$

$$x_j + x_i \le 1 \quad \forall j,i \in I: \mathrm{d}(j,i) < D_{min}$$

$$v_j^n = v_0^n\left(1 - \sum_{i\in I/j} x_i w_{ij}^n\right) \quad \forall i,j \in I$$

$$\hat{P}_i^n \le P_{rate} x_i \quad \forall i \in I$$

Power curve piecewise linearization

$$\sum_{l\in L}\eta_{i,l}^n = 1 \quad \forall i \in I \quad \forall l \in L$$

$$\sum_{l\in L}\eta_{i,l}^n v_{s,l} \le v_i^n \le \sum_{l\in L}\eta_{i,l}^n v_{h,l} \quad \forall i \in I$$

$$\hat{P}_i^n \le \mathrm{P}\left(\sum_{l\in L}\eta_{i,l}^n v_{m,l}\right) \quad \forall i \in I$$

Regular layout constraints

$$x_i \le \sum_{j\in \tilde{I}_i} x_j \quad \forall i,j \in I$$

- **Phase 2 Continuous model**

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

$$s.t. (x_{i,1}, x_{i,2}) \in A(x_i) \quad \forall i \in I$$

$$(x_{i,1}^1, x_{i,2}^1) \in A(x_i) \quad \forall i \in \bar{I}$$

$$(x_{i,1} - x_{j,1})^2 + (x_{i,2} - x_{j,2})^2 \le D_{min}^2 \quad \forall i,j \in I$$

Rotation Constraint

$$x_{i,1} = x_{i,1}\cos\theta - x_{i,2}\sin\theta \quad \forall i \in I$$

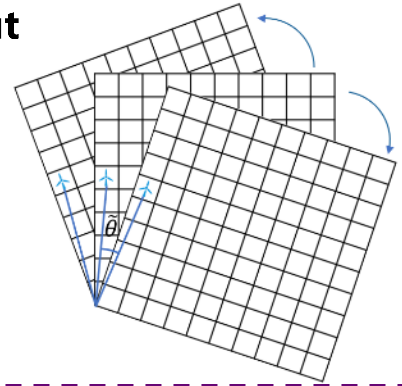
$$x_{i,2} = x_{i,1}\sin\theta + x_{i,2}\cos\theta \quad \forall i \in I$$

$$v_j^n = v_0^n\left(1 - \sqrt{\sum_{i\in I/j} x_i \left(w_{ij}^n\right)^2}\right) \quad \forall i,j \in I$$

$$x_{j,1}^k = x_{i,1}^1 + (k-1)\chi \quad \forall i,j \in \bar{I} \quad \forall k \in [1, y]$$

$$x_{j,2}^k = x_{i,2}^1 \quad \forall i,j \in \bar{I} \quad \forall k \in [1, y]$$

Regular layout constraints



Zehai Huang, **X. Shen***, etc., Two-Phase Micro-siting for Offshore Wind Farms with Regular Layout, submitted to IEEE Trans. on Sustainable Energy, R1

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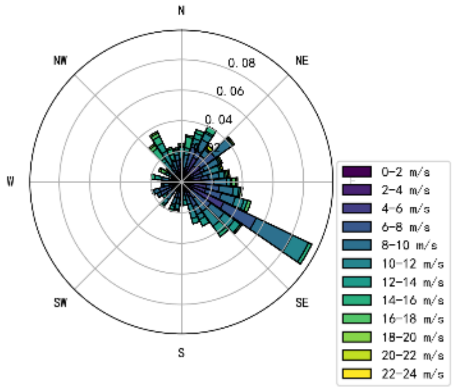
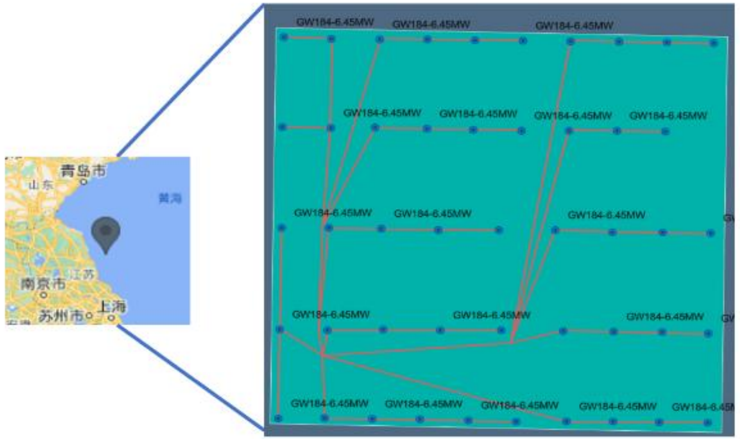
➢ Micro-sitting model for WTs considering regular layout

- Actual Cases

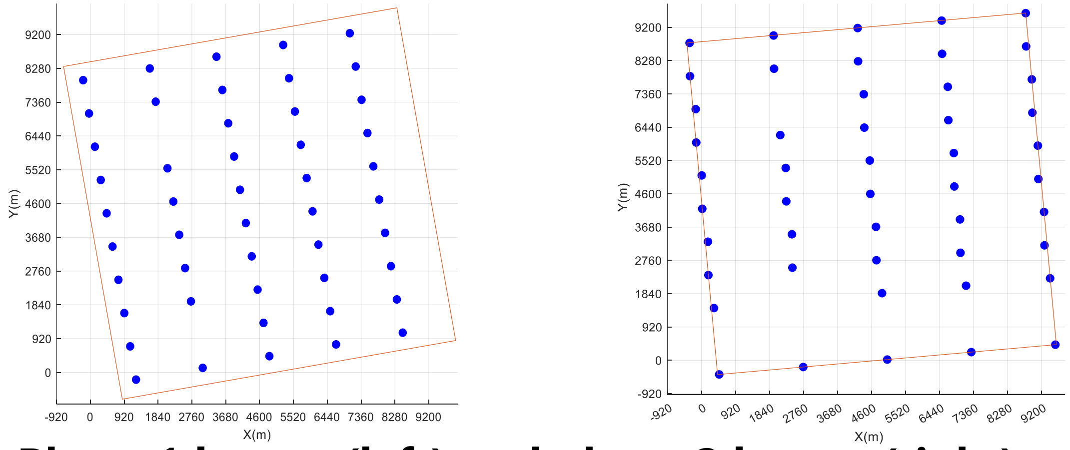


Actual wind rose



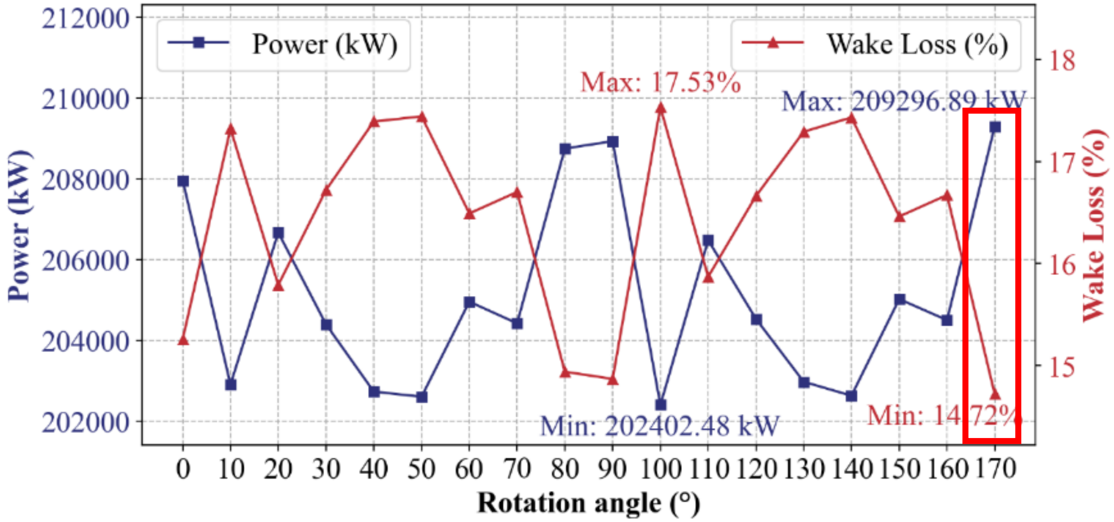
Jiangsu Dafeng H4 OWF

- Optimization results



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

- Phase 1 result



- Phase 2 result comparison

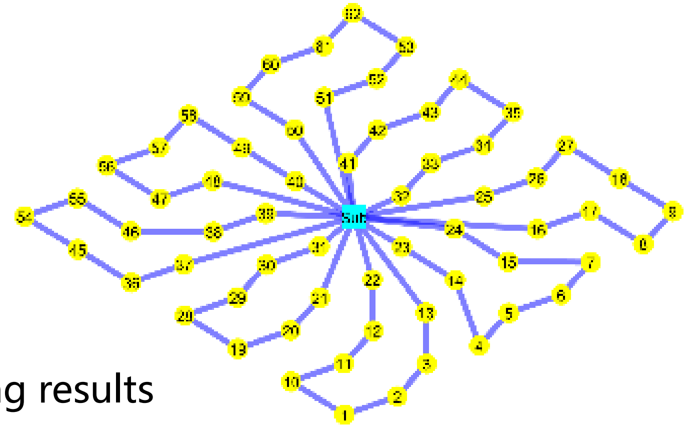
Scheme	Wake Model	Power generation (kW)	Wake loss(%)
Existing approach	Cosine	207142.2	15.60
Proposed approach	Cosine	216385.7	**11.83**

Zehai Huang, **X. Shen***, etc., Two-Phase Micro-siting for Offshore Wind Farms with Regular Layout, submitted to IEEE Trans. on Sustainable Energy, R1

Key Issue

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

Improved CVRP-based ECS planning

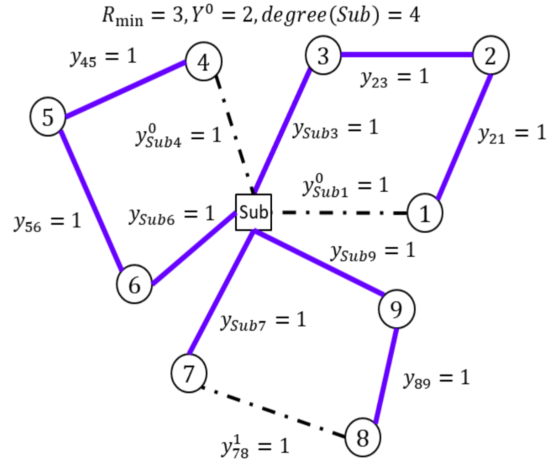


ECS planning results

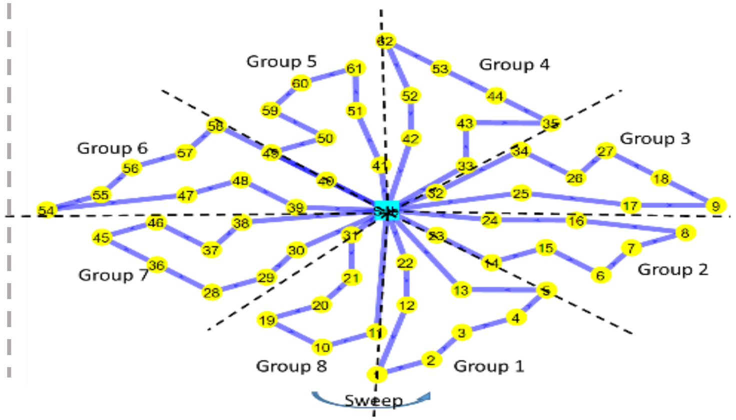
$$\min_{x,P} \sum_{(i,j)\in L} c_{ij}x_{ij} + \eta \sum_{(i,j)\in L} r_{ij}{P_{ij}}^2$$

$s.t.$
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

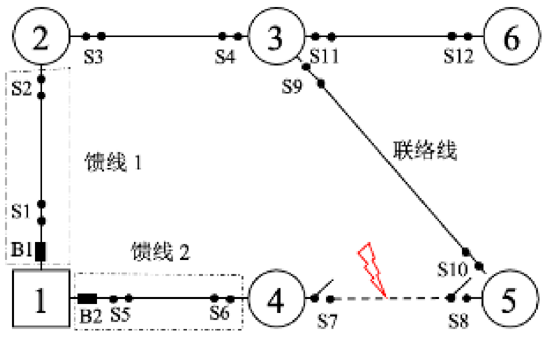
Key Issue

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

ECS planning with reliability constraints

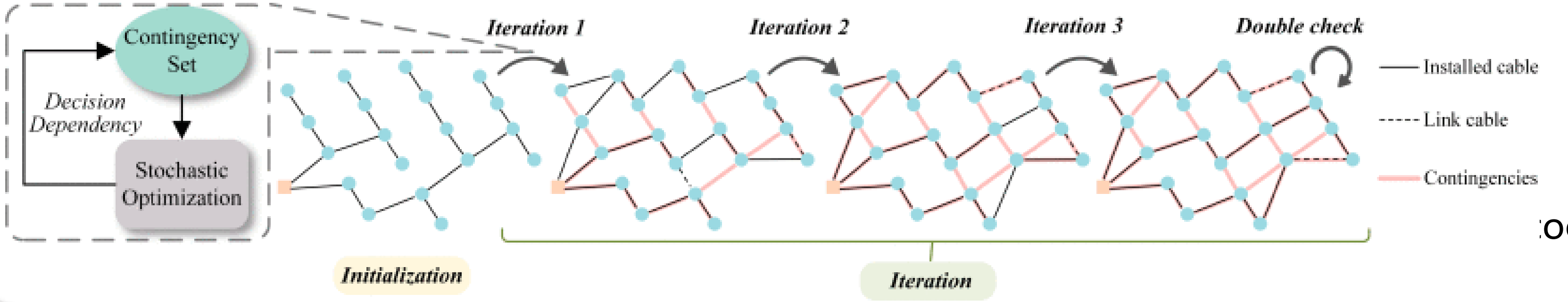
$$\min C_{cap} \sum_{ij \in \Psi_B} d_{ij} l_{ij} + \omega EEND$$

$s.t.$ 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**

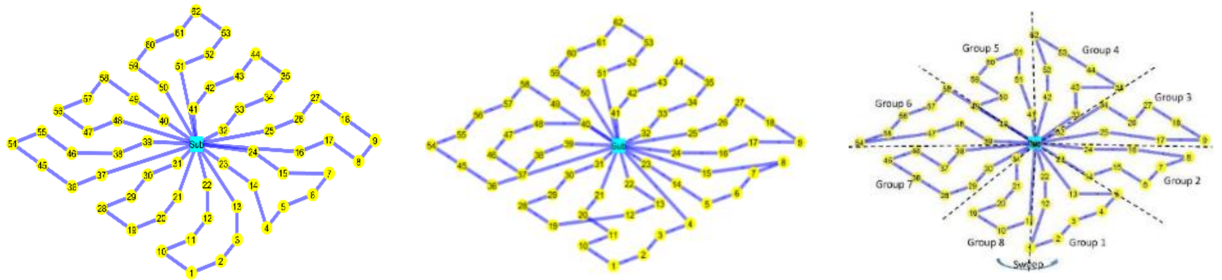
Power network expansion planning model

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**)

Related Research 2 » Radial ECS planning

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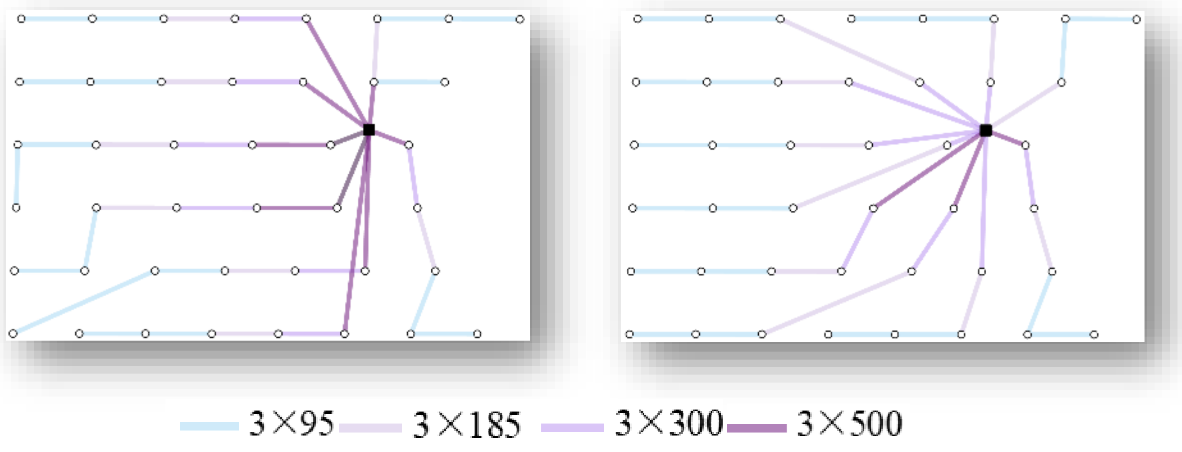
Tsinghua Shenzhen International Graduate School

- **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.

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

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

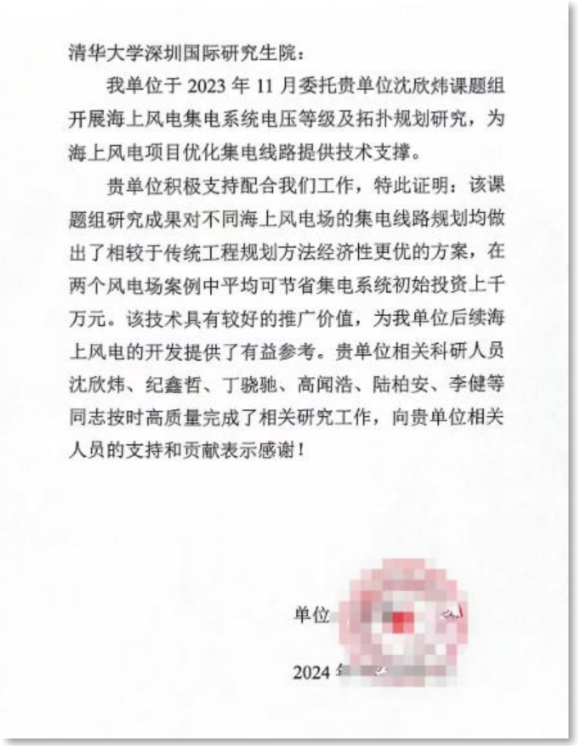
Results for ECS topology and cable type selection



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


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撑。

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、丁骁驰、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

Received a letter of thanks from the design institute

[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**

Operational and maintenance cost

$$\min \; C_{INV} + C_{O\&M} + C_{REL}$$

Cable investment cost

Wind curtailment cost due to contingencies

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

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:**

Operational and maintenance cost

$$\min \quad C_{INV} + C_{O\&M} + C_{REL}$$

Cable investment cost

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:

$\tilde{\Upsilon} = \upsilon_0, \Omega = \omega_n$;
Apply BD strategy to solve $(\hat{x}, \hat{y}^{\upsilon,\omega}) = \arg\min_{x,y^{\upsilon,\omega}} \tilde{\mathcal{P}}_{\tilde{\Upsilon},\Omega}$ to $\epsilon \le \epsilon_0$;
$\hat{\Upsilon} = \{\upsilon_i | \upsilon_i \in \Upsilon \cup \upsilon_0, \hat{x}_i = 1\}$, $x_{ws} = \hat{x}$, $Ind = 0$;

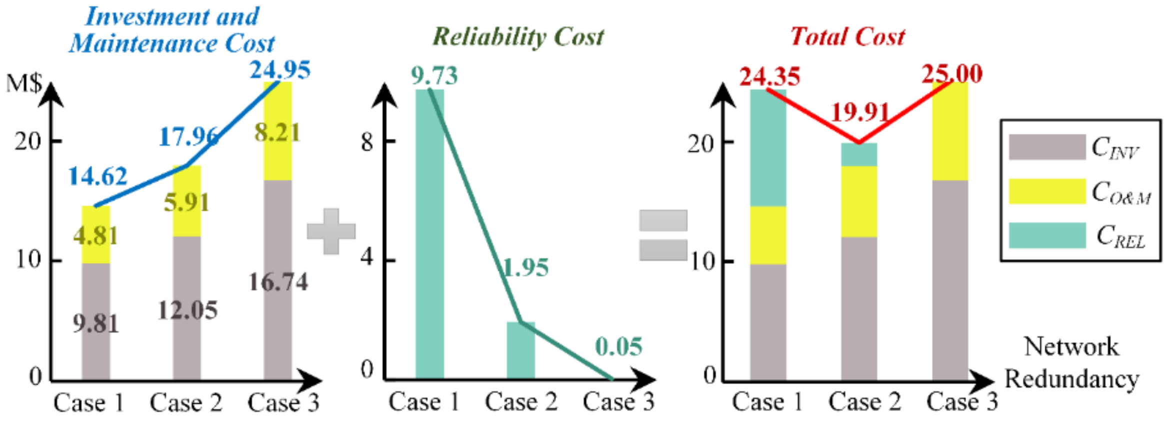
Iteration:

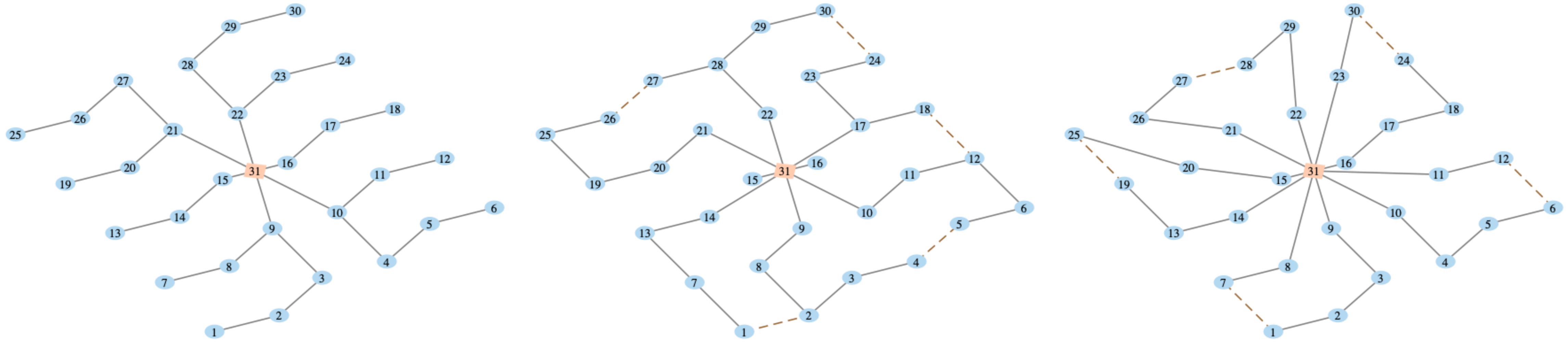
while $Ind == 0$ **do**
  $\tilde{\Upsilon} = \tilde{\Upsilon} \cup \hat{\Upsilon}$;
  Apply BD strategy to solve $(\hat{x}, \hat{y}^{\upsilon,\omega}) = \arg\min_{x,y^{\upsilon,\omega}} \tilde{\mathcal{P}}_{\tilde{\Upsilon},\Omega}$ to $\epsilon \le \epsilon_0$ with warm-start point x_{ws};
  $\hat{\Upsilon} = \{\upsilon_i | \upsilon_i \in \Upsilon, \hat{x}_i = 1\} \cup \upsilon_0$, $x_{ws} = \hat{x}$;
  if $\hat{\Upsilon} == \hat{\Upsilon} \cap \tilde{\Upsilon}$ **then**
    Apply BD strategy to solve $(x^*, y^{\upsilon,\omega *}) = \arg\min_{x,y^{\upsilon,\omega}} \tilde{\mathcal{P}}_{\tilde{\Upsilon},\Omega}$ to optimality with warm-start point x_{ws};
    $\Upsilon^* = \{\upsilon_i | \upsilon_i \in \Upsilon, x_i^* = 1\} \cup \upsilon_0$;
    if $\Upsilon^* == \Upsilon^* \cap \tilde{\Upsilon}$ **then**
      $Ind = 1$;
    else
      $\tilde{\Upsilon} = \tilde{\Upsilon} \cup \Upsilon^*$, $x_{ws} = x^*$;
    end if
  end if
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

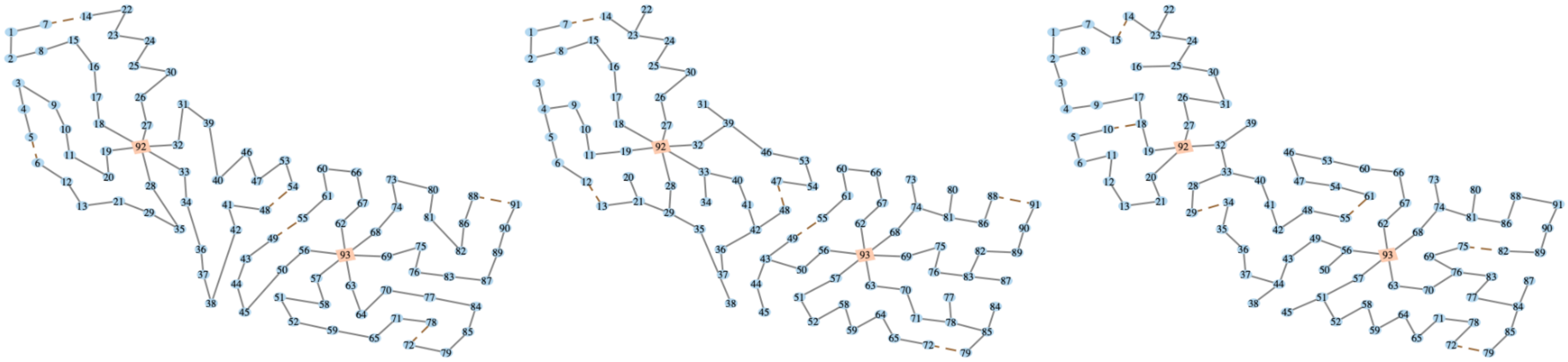
Related Research 2 ❯❯ ECS planning with mixed topology

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



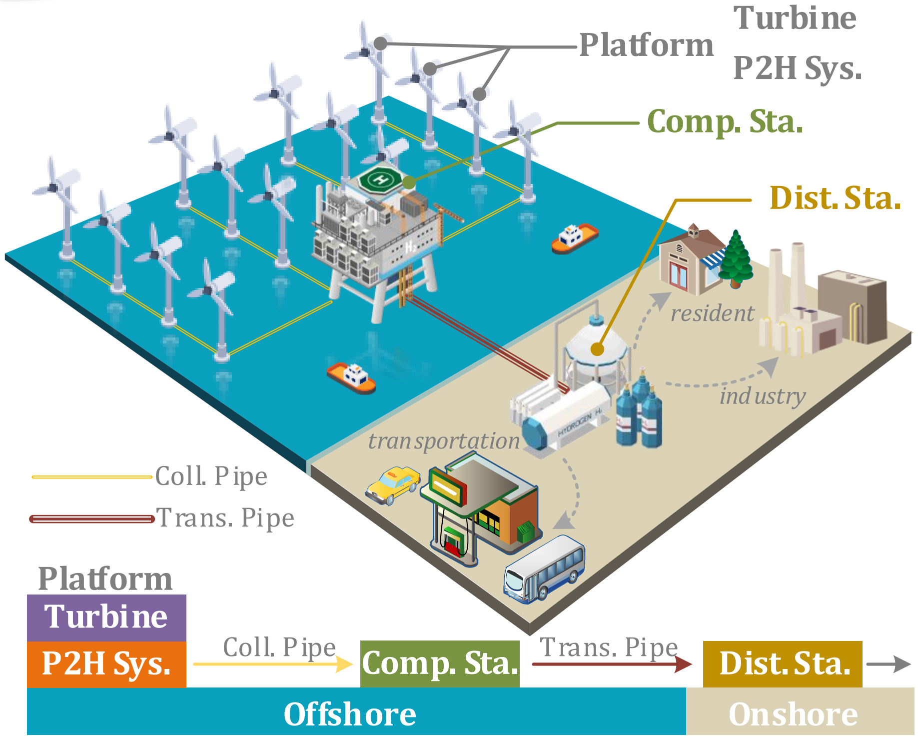
(a) Case 4: Sweep + CWS planning

(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**

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

Equivalent annual cost (EAC)

Annual hydrogen production (AHP)

Platform location/devices capacity

➢ **Constraints**

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

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

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

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

$$EAC_{\mathrm{TAX}} = c_{\mathrm{TAX}}(c_{\mathrm{H}} AHP - AC_{\mathrm{OM}})$$

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

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

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

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

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

- 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**

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

- **Constraints**

  - Operation current constraint
  - System capacity constraint

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

$$P_{k,i}^{\mathrm{P2H}} \le Q_i^{\mathrm{P2H}}, \quad \forall k \in K, \forall i \in N$$

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

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

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

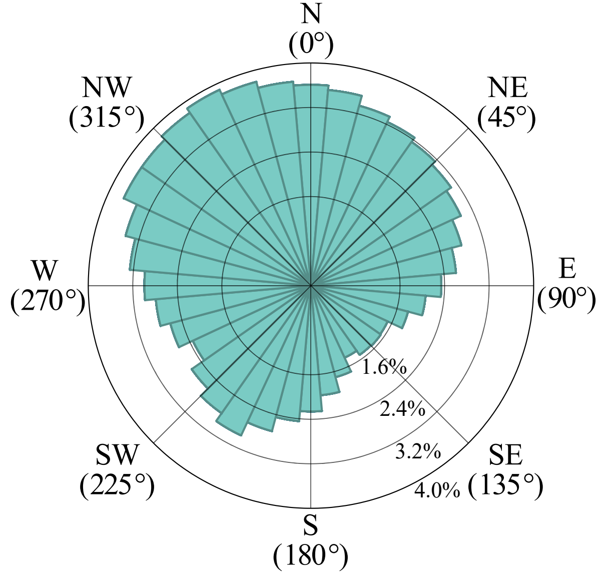
$$P_i^{\mathrm{ELE}} = N^{\mathrm{C}} U_i^{\mathrm{C}} I_i^{\mathrm{P2H}}, \quad \forall i \in N \qquad U_i^{\mathrm{C}} = E + U_i^{\mathrm{O}} + U_i^{\mathrm{ACT}} \qquad h_i^{\mathrm{P2H}} = \frac{N^{\mathrm{C}} I_i^{\mathrm{P2H}} \eta^{\mathrm{F}}}{2F}, \quad \forall i \in N$$

[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

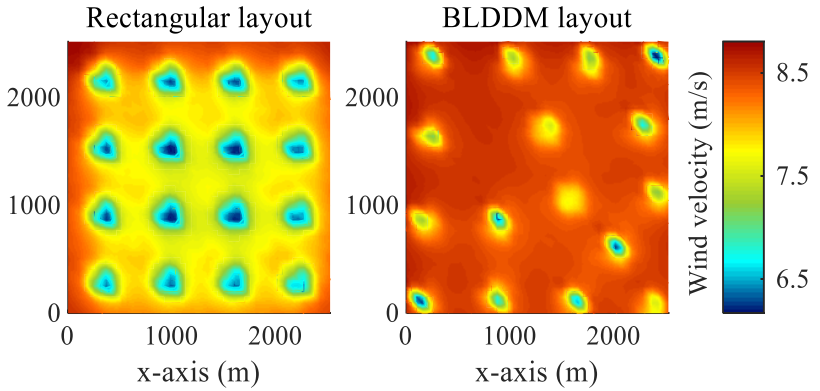


- ✓ The initial layout of the platform adopts **rectangular layout**

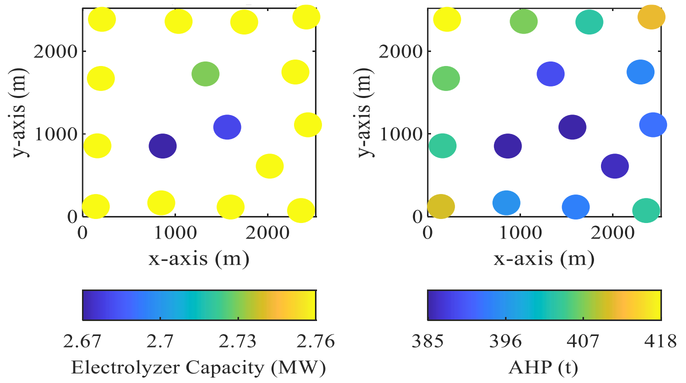
☐ Platform layouts

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

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

TPLs cost — GPLs cost

$\xi_{i,j}$: *Investment decision variables of candidate GPL (binary variables)*

x^{GS},y^{GS}: *Coordinates of gathering station nodes (continuous variables)*

■ Constraints

Gathering station location range constraints

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

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

Spanning tree constraints

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

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

Hydrogen flow balance constraints

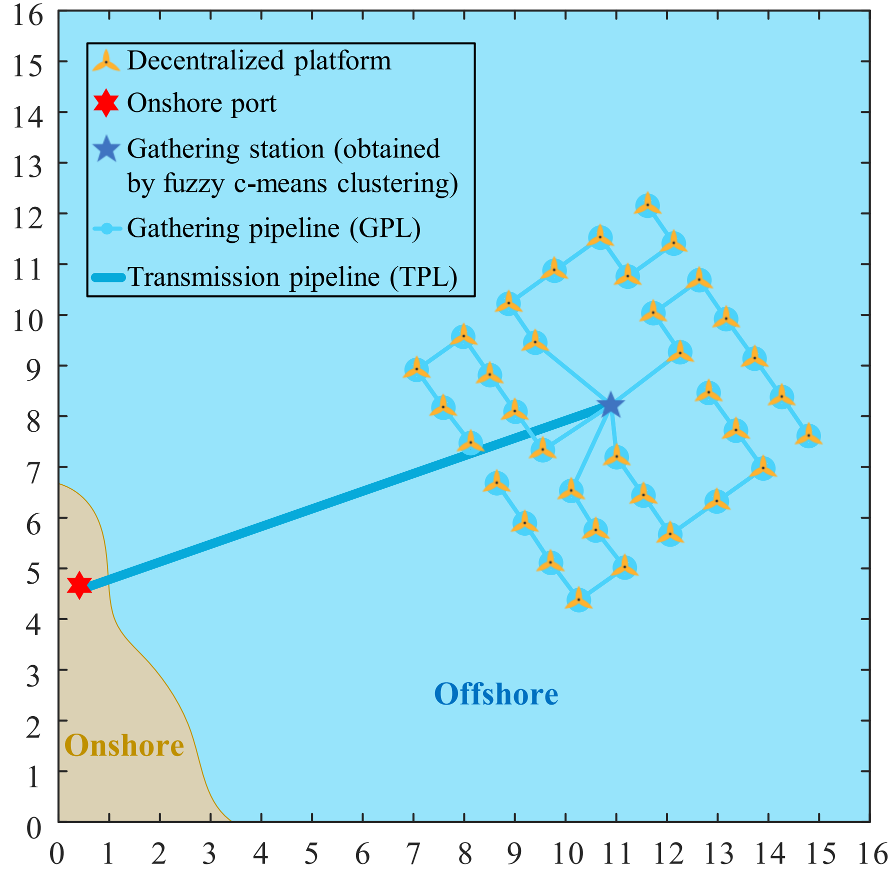
$| F_{i,j} | \le \xi_{i,j}\bar{F}_{i,j},\ \forall \{i,j\} \in L$

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

Engineering constraints

$\xi_{i,j} + \xi_{m,p} \le 1,\ \forall \{i,j\} \times \{m,p\} \ne \varnothing, \{i,j\},\{m,p\} \in L$

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



Topology for decentralized OWHS

[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 Planning for Decentralized Offshore Wind-Hydrogen System: A Two-Phase Optimization Approach. IEEE PES General Meeting, 2025.

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

First Phase: Grid-based Layout Co-planning

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

(x^{GS*},y^{GS*}) Coordinates of gathering station

$\xi_{i,j}^*$ Decision variables of candidate GPL

Second Phase: Gathering Station Location Refinement

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

[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 Planning for Decentralized Offshore Wind-Hydrogen System: A Two-Phase Optimization Approach. IEEE PES General Meeting, 2025.

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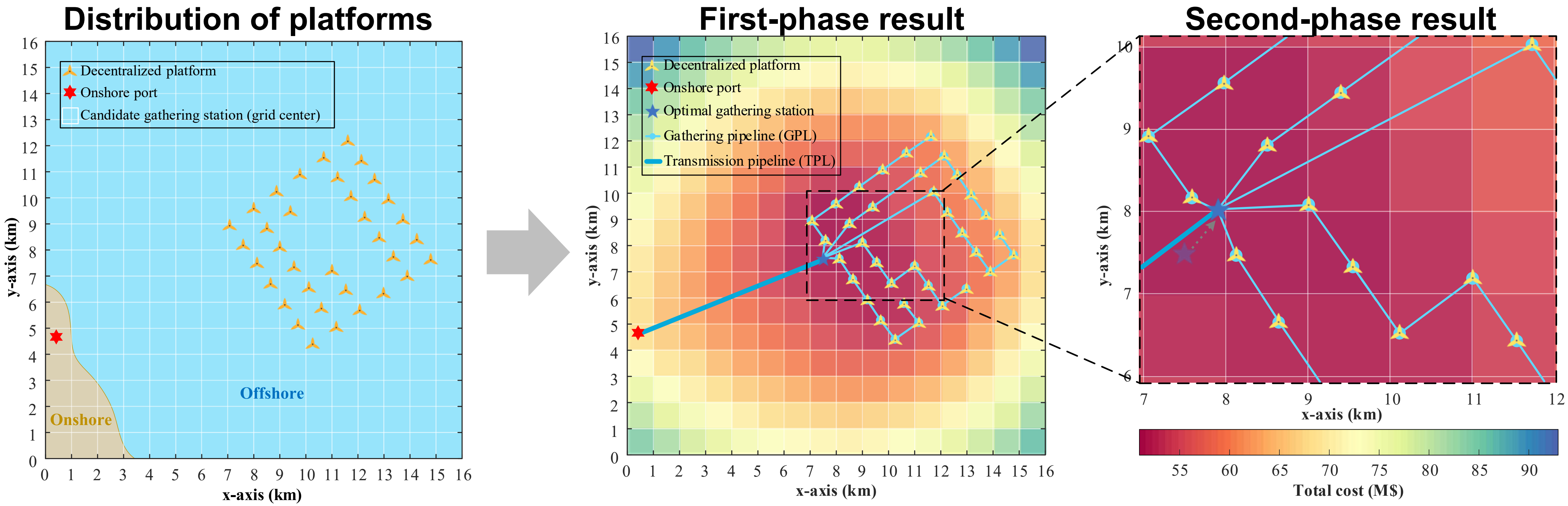
◻ Co-optimization model for pipeline and hydrogen gathering station



- ◻ **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 Planning for Decentralized Offshore Wind-Hydrogen System: A Two-Phase Optimization Approach. IEEE PES General Meeting, 2025.

Related publications/patents

◆ Selected papers

[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]**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," Journal of Modern Power System and Clean Energy, 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] Wenhao Gao, **X. Shen***, etc., Optimization planning of offshore wind power collection system based on large-scale mixed integer programming, AEPS, R2.

[11] Zehai Huang, **X. Shen***, etc., Two-Phase Micro-siting for Offshore Wind Farms with Regular Layout, submitted to Applied Energy, R1.

◆ Patents

[1] 202211741349.1, Reliability assessment and planning method for offshore wind farm collection system

[2] 202310058191.6, a planning and design method for double-sided ring collector system in offshore wind farms

[3] 202310062915.4., Linear power flow model, its optimization method and distribution network operation stability evaluation method

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