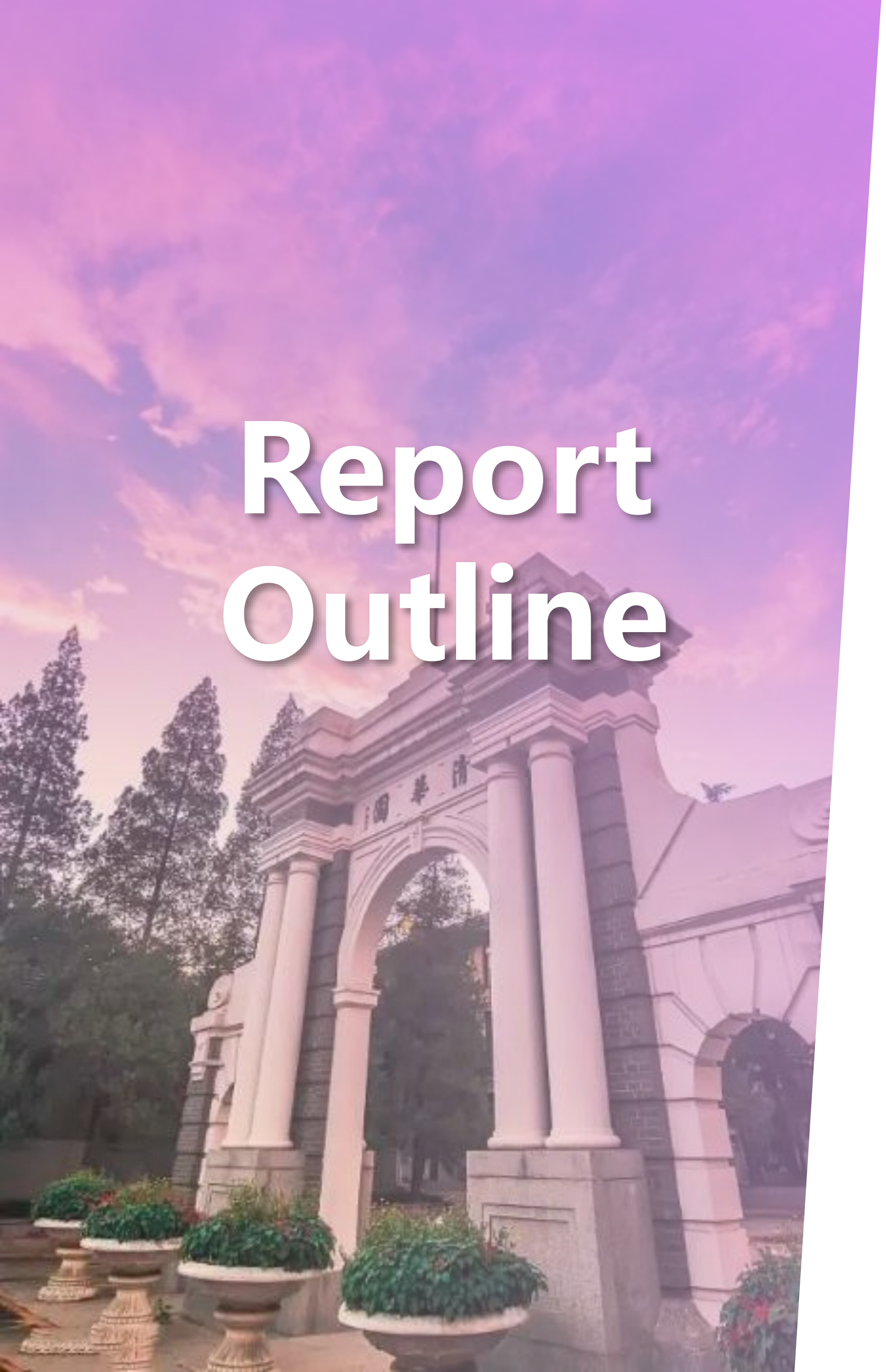
清华大学深圳国际研究生院
Tsinghua Shenzhen International Graduate School

Seminar by Universities in the Greater Bay Area
7th April, 2025, at HKU

Large-scale Offshore Wind Farm Planning based on Complex Combinatorial Optimization

Xinwei Shen

Institute for Ocean Engineering
Tsinghua Shenzhen International Graduate School



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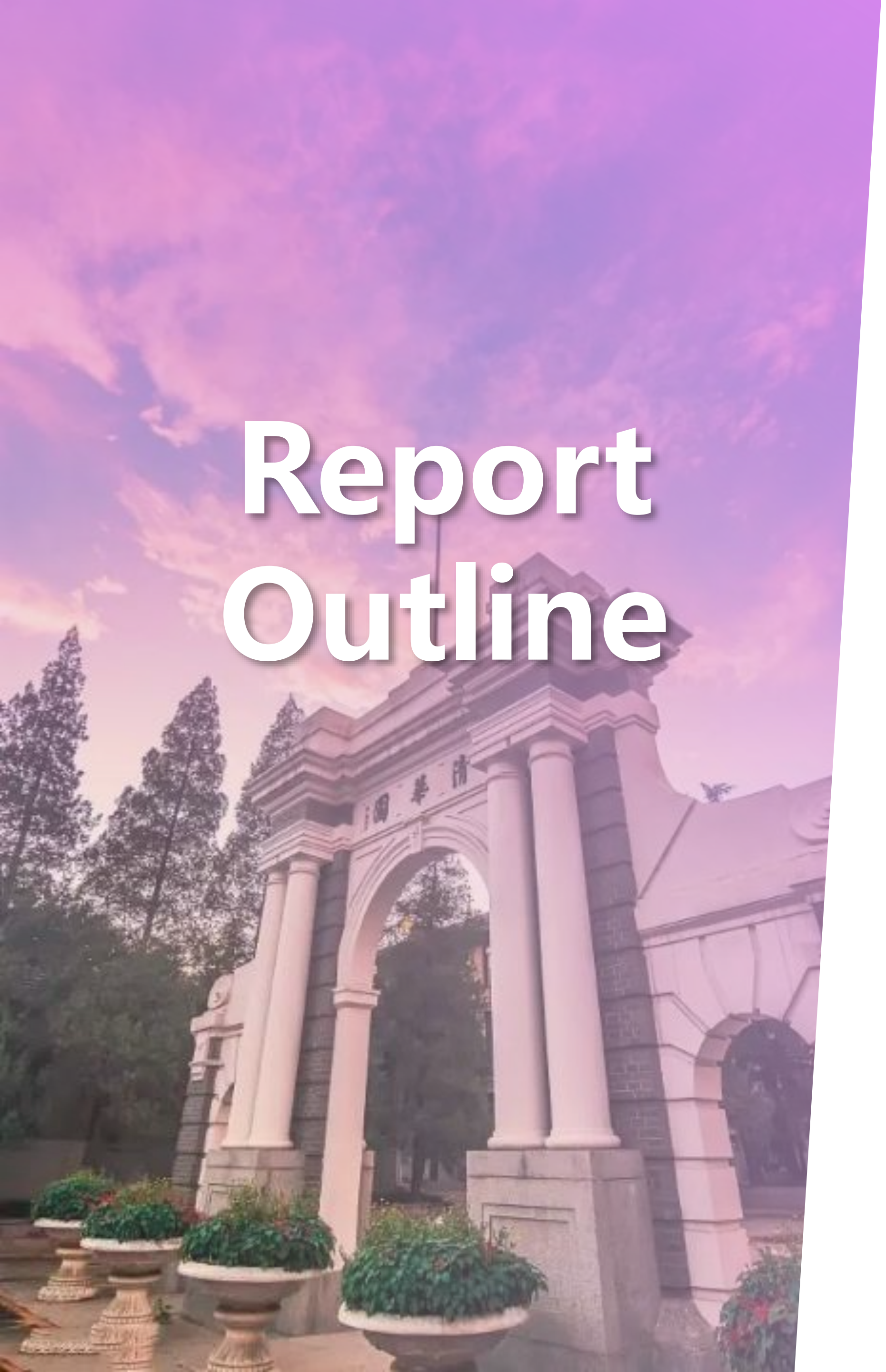


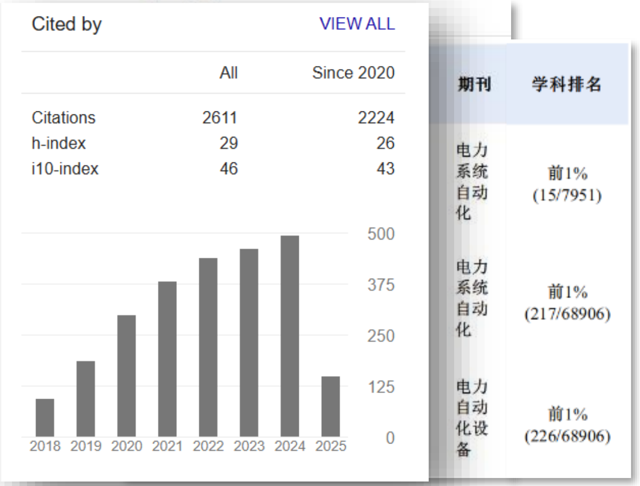
Report Outline

Personal Profile

Tsinghua Shenzhen International Graduate School

Xinwei Shen (沈欣炜)

Assistant Professor,
Institute for Ocean Engineering
Tsinghua SIGS
(2021.11-to date)



●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 2600+, 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)

Personal Profile

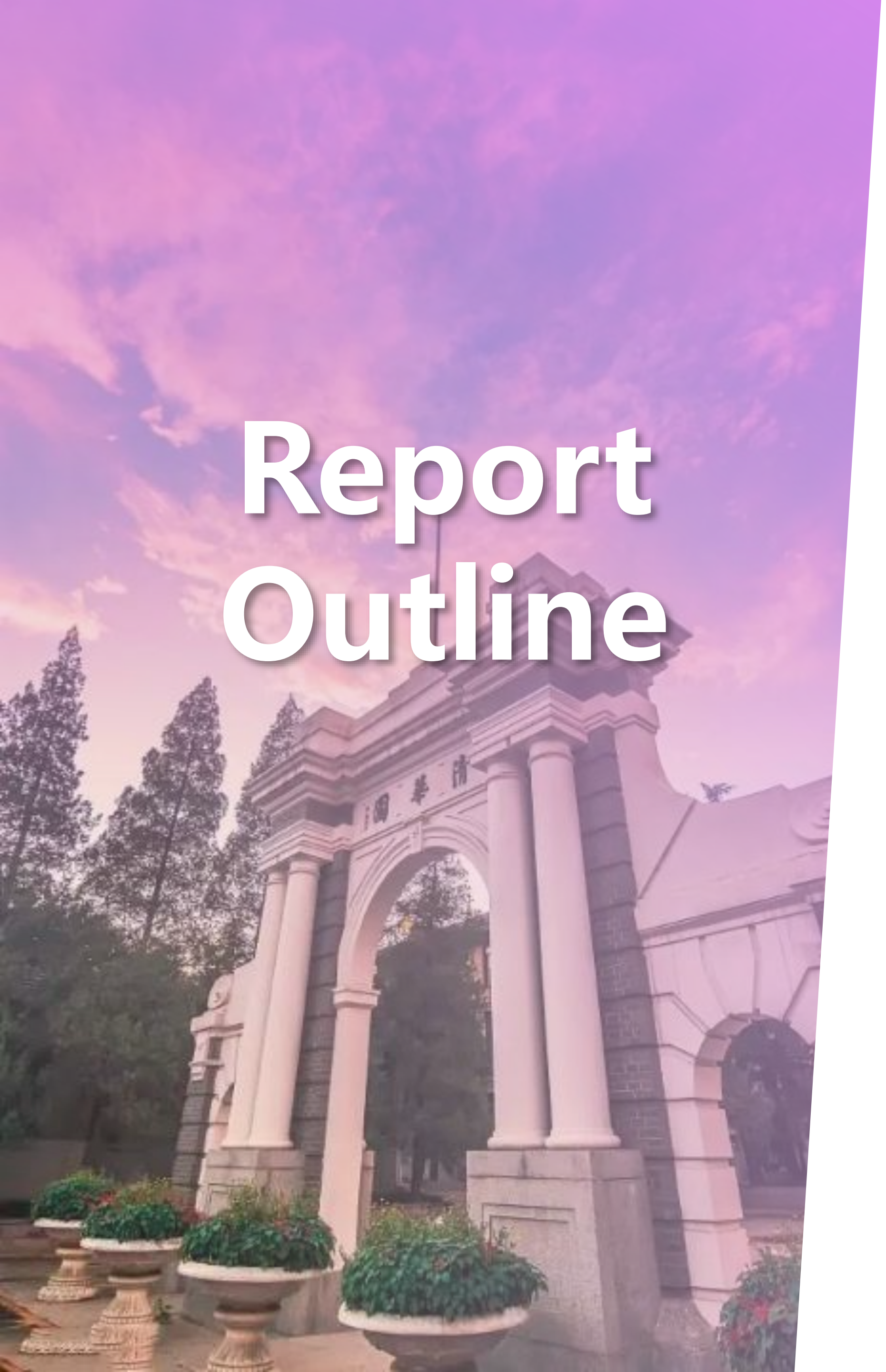
清华大学深圳国际研究生院
Tsinghua Shenzhen International Graduate School

●Academic Services:

- ◻IEEE Senior Member/CSEE Member/CES Senior Member
- ◻IEEE Energy Internet Coordinating Committee (EICC)
- ◻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

Background ❯❯ Offshore Wind Power Development

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National encouragement

- **《2030 Carbon peak action plan》，《2024 Energy work guidelines》**
- 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 appiled.
- **16+ MW** have also been released.
- **1 Trillion USD** will flow into the global offshore wind industry before 2035.

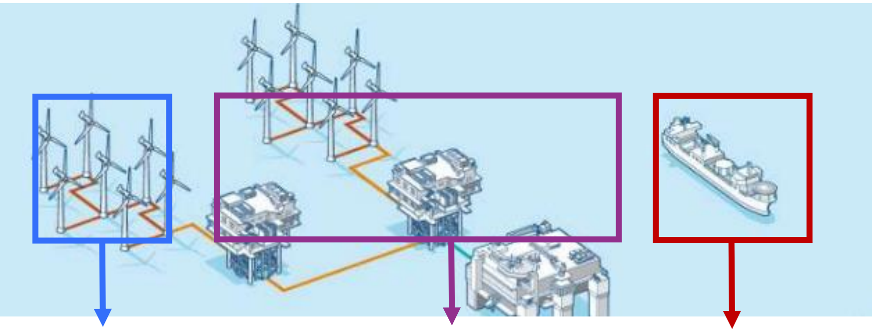
Deep-sea floating

- **80%** offshore wind resources are located in >60 m deep water.
- Offshore wind power develop into deep sea with **complex marine environment, high cost, difficulty in power delivery, and high failure rate**.

The offshore wind industry has great potential!

Offshore wind power: LCOE

- Levelized Cost of Energy (LCOE) reflects the economic benefits of offshore wind power
- 2024 Offshore Wind Power China's **LCOE ≈ 0.46 CNY/kWh**[1] **> Coal-fired power (0.26 CNY/kWh)**
- Along with **subsidies decline, deep-sea development**, **to reduce LCOE is more urgent**



Reduce costs/ increase revenue!

LCOE = (Construction costs + Devices investment + O&M costs) / Power generation over entire life cycle

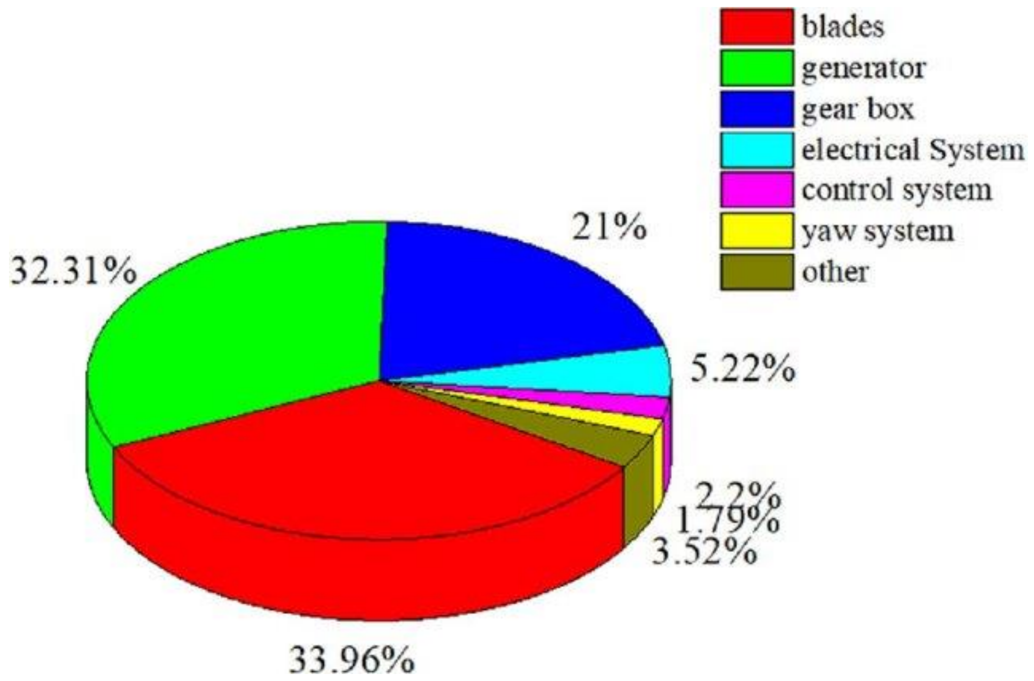
Increase power generation!

Enhance Benefits

- **Increase power generation: optimize the layout and reduce wake (micro-siting)**
- **Reduce costs/increase revenue: Optimizing electrical collector system, hydrogen production**

Devices	Failure rate (times/Year)	MTTR(Hour)
Gearbox	1.9	244.91
Pitch	15.3	144.31
dynamo	1.84	100.92
Hydraulic system	1.8	37.94
Yaw system	0.22	41.21
Medium voltage circuit breaker	0.025	240
Medium voltage switch	0.025	240
Low voltage contactor	0.0667	240
Cabin transformer	0.0131	240
1kmcable	0.015	1440

Failure rate and MTTR of devices in offshore wind farms[1][2]



Sector chart of downtime ratio of each subcomponent of offshore wind turbine

Offshore devices are complex and have high failure rates. The O&M of offshore wind farms has a window period and a long mean time to repair (MTTR), resulting in serious economic losses.

[1] Ossai C I, Boswell B, et al. A Markovian approach for modelling the effects of maintenance on downtime and failure risk of WT components. Renewable energy, 2016, 96: 775-783.
[2] WARNOCK J, MCMILLAN D, PILGRIM J, et al. Failure Rates of Offshore Wind Transmission Systems. Energies, 2019, 12(14): 2682. DOI:10.3390/en12142682.
[3] Zhou, F., Tu, X., & Wang, Q. Research on offshore wind power system based on Internet of Things technology. International Journal of Low-Carbon Technologies, 2022, 17, 645-650.

Research status » Industry Practices

- Applying mathematical optimization in offshore wind farm planning can bring 10-15 M EUR economic benefits[1].
- As early as 2019, Vattenfall accumulated benefits of 150 M EUR in multiple wind farms[2].

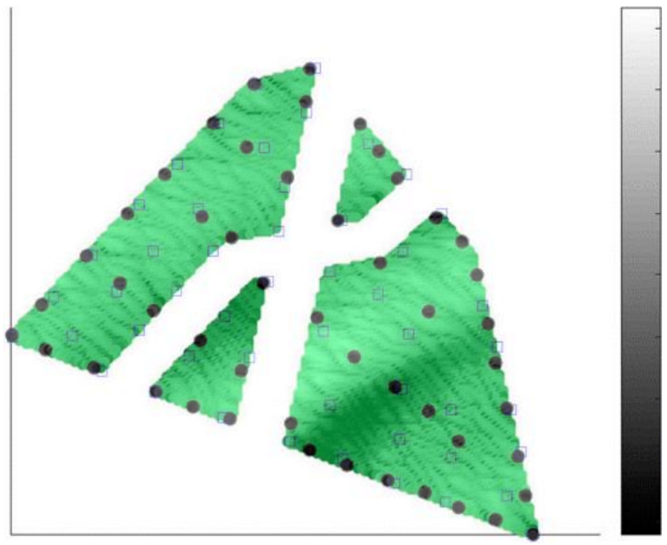
Economic benefits of optimal planning

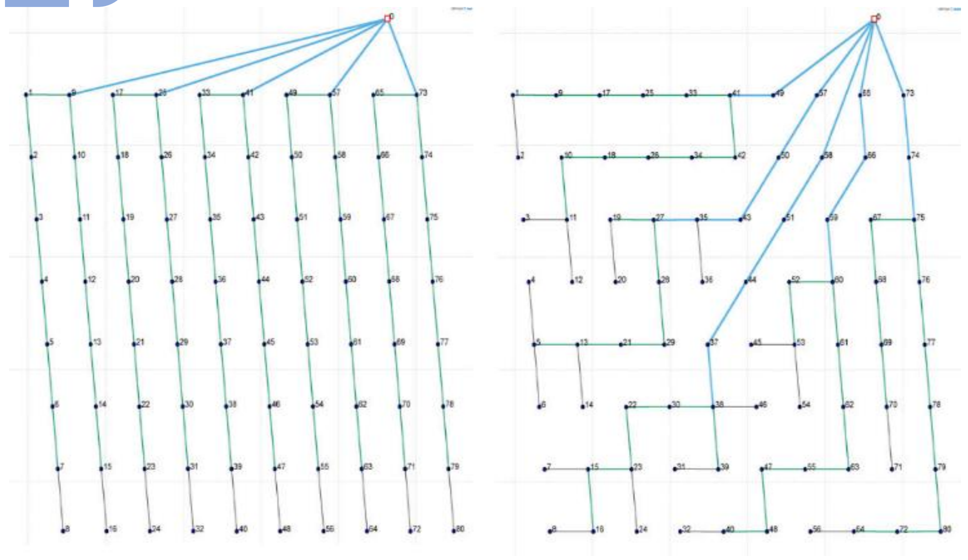
micro-siting

Increase generation
2.6 M EUR

Reduce steel
10 M EUR

Electrical collector system planning
1.7 M EUR





Mathematical optimization can produce huge benefits in offshore wind development!

[1] Fischetti M, Kristoffersen JR, Hjort T, Monaci M, Pisinger D. **Vattenfall optimizes offshore wind farm design**. INFORMS Journal of Applied Analytics, 2020, 50(1):80–94.
[2] Fischetti M, Fischetti M. **Integrated Layout and Cable Routing in Wind Farm Optimal Design**. Management Science, 2022: mnsc.2022.4470.

Research status » Micro-sitting for wind turbines (WTs)

- Wake Model
  - Parametric model
    - Jensen Model
    - Larsen Model
    - Frandsen Model
  - CFD model

$$\min_{x} C^{inv}(x) + C^{wake}(x)$$
$$s.t.\ G(x) \le 0$$
$$x = (x_1, \ldots x_i \ldots x_N)^{\mathrm{T}}$$

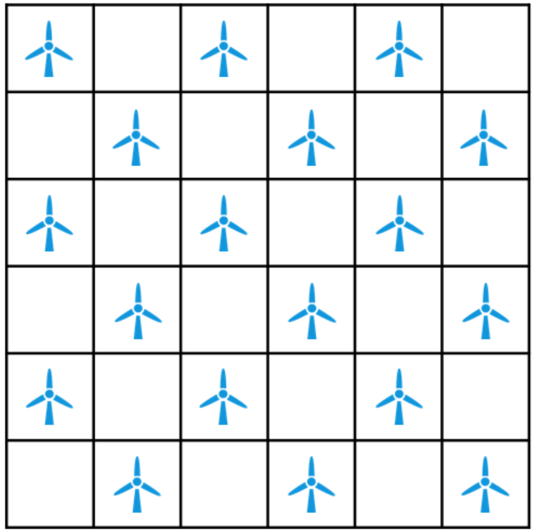
C^{inv}: WT investment cost

C^{wake}: Wake effect cost

$G(x) \le 0$: Construction-related constraints

Solution[2]	Method	Characteristics
	Mathematical optimization	**Strong optimality**; **Curse of dimensionality**
	Heuristics algorithm	**Fast calculation time**; Solution inconsistency; **local optimum**

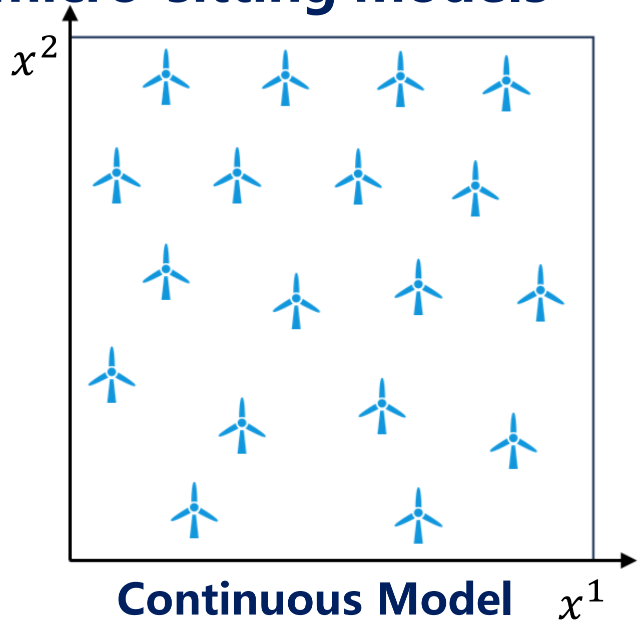
Classification of micro-sitting models[1]



Grid-based Model

$x_i \in \{0,1\}$ indicates whether grid i is selected to build a WT ($x_i = 1$ is selected)

Mixed Integer Programming MIP



Continuous Model

$x_i = (x_i^1, x_i^2)$ indicates WT i Coordinates

Nonlinear Programming NLP

[1] Hou P, Zhu J, et al. A review of offshore wind farm layout optimization and electrical system design methods. Journal of Modern Power Systems and Clean Energy, 2019, 7(5): 975-986.
[2] Zuo T, Zhang Y, et al. A review of optimization technologies for large-scale wind farm planning. IEEE Trans. on Industrial Infor., 2022, 19(7): 7862-7875.

Research status ›› Electrical collector system (ECS) planning

$$\min C^{inv}(x) + \sum_{\xi^h \in \varphi^h} C^{rel}(x, y^h, \xi^h)$$

$$s.t.\ G(x, y^h, \xi^h) \leq 0$$

$$x = (x_1, \dots x_i \dots x_L)^{\mathrm{T}}$$

C^{inv}: ECS construction costs

C^{rel}: Reliability-related costs

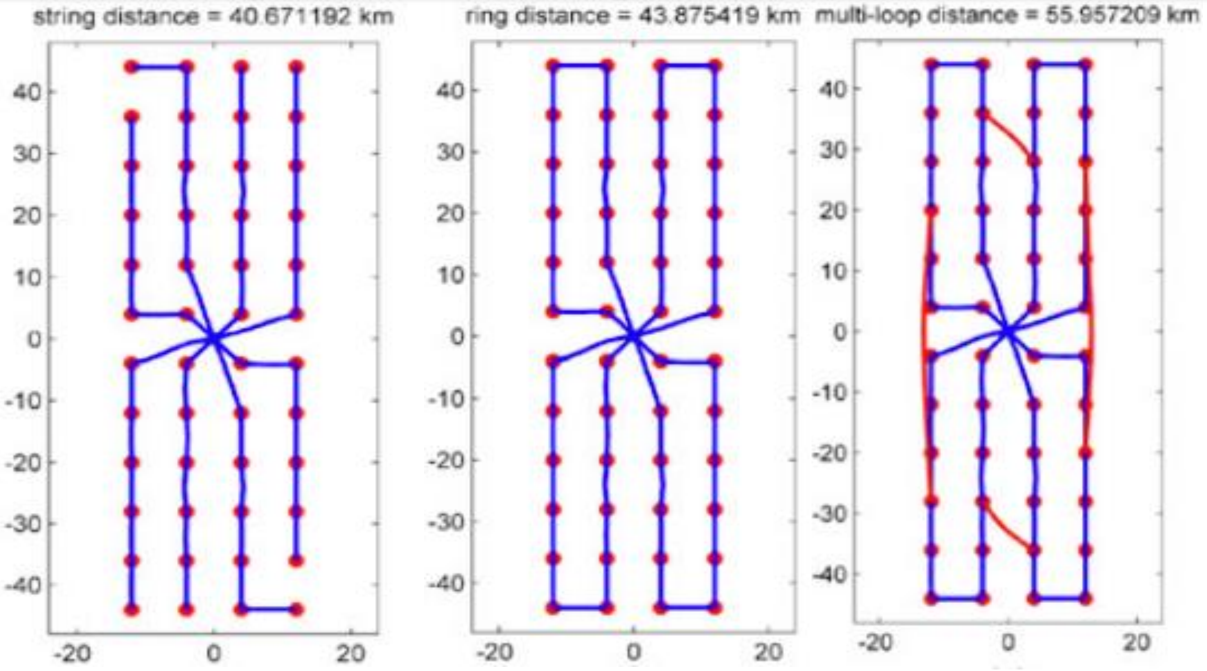
$x_i \in \{0,1\}$: Indicates whether to build a submarine cable i

y^h: Operation strategy under the failure scenario h

ξ^h: Random parameters such as failure rate

$G(x) \leq 0$: Restrictions on submarine cable construction

- There are different optimal ECS topologies for different **cable failure rate** and **MTTR**[1].
- **Joint planning** for ECS **topology**, **selection** and **reliability** can obtain huge **Economic Benefits**.



Radial Cable length=40.67km

Ring Cable length=43.87km

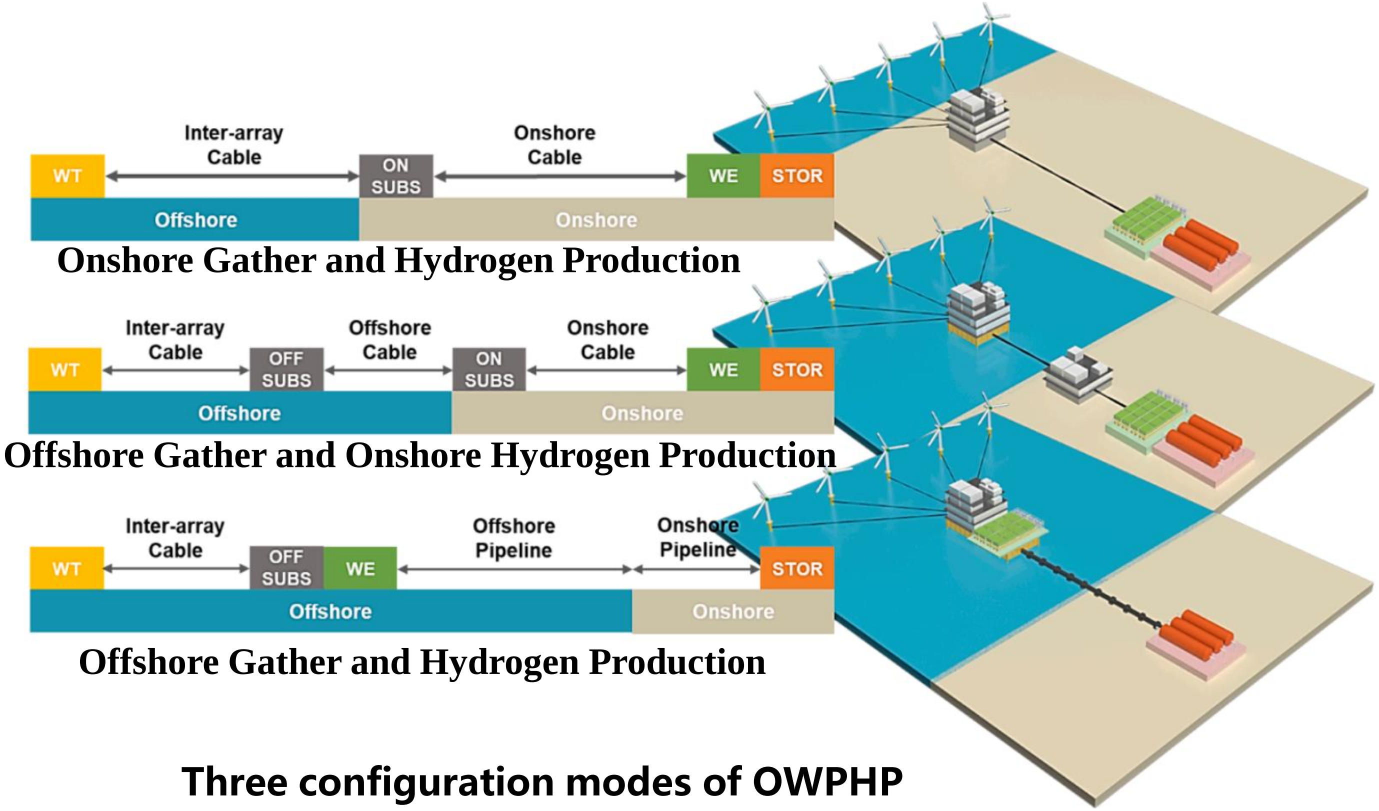
Multi loops Cable length=55.96km

[1] X. G, S. K, BC Pal. Optimal Wind Farm Cabling. IEEE Transactions on Sustainable Energy, 2018,9(3):1126-1136.

- Current research is mostly focused on economic analysis, but not mathematical optimization.
- **Industry practice**: Dolphyn, Dogger Bank D, H2Sines.Rdam, H2Maasvlakte, Gigastack, and HT 1.
- It is important to reduce the costs of Offshore Wind-Powered Hydrogen Production (OWPHP) by optimization within the current level of technology.

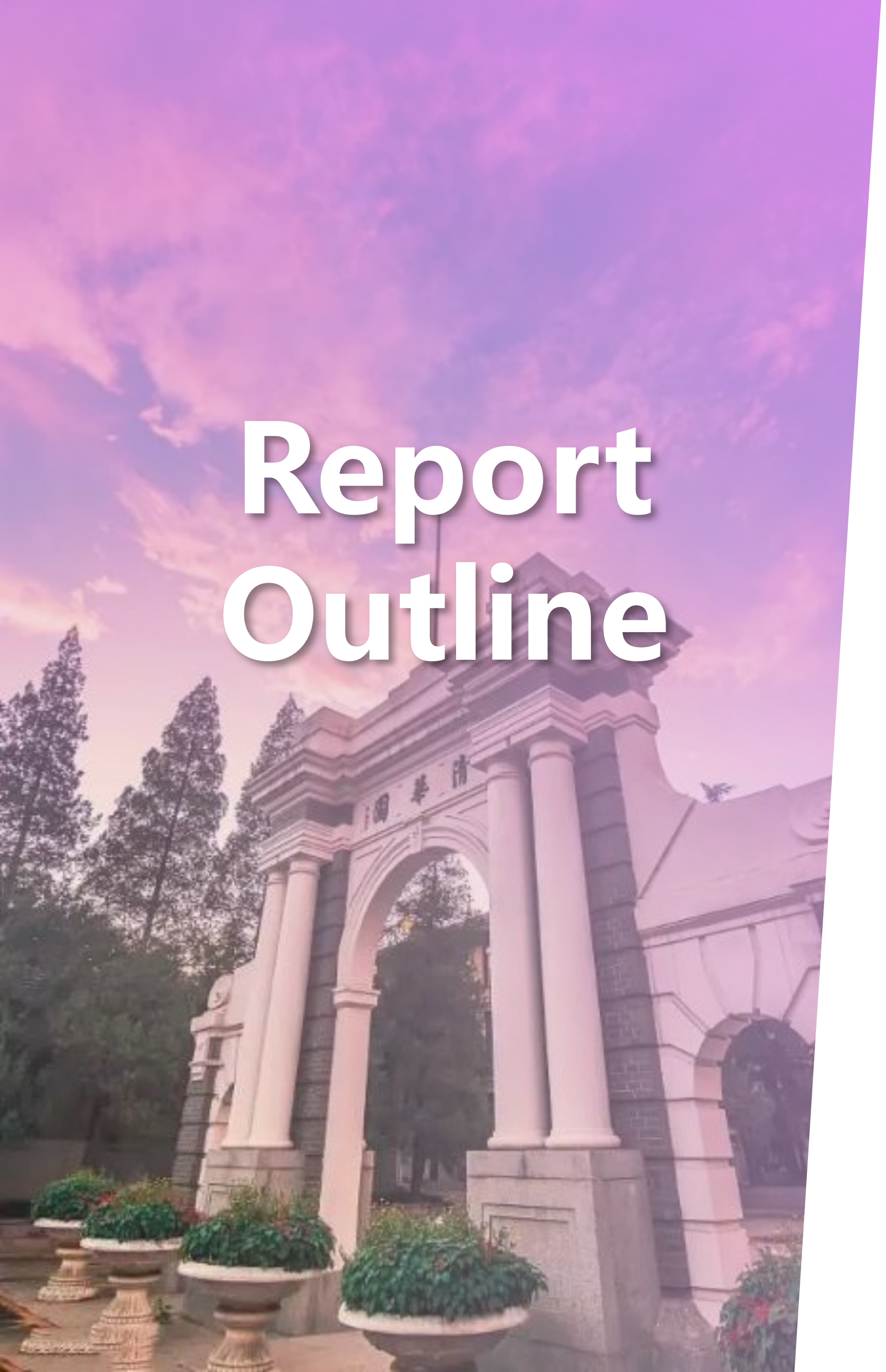
Distance to shore

- nearshore
- medium to far
- far and deep-sea



Three configuration modes of OWPHP

[1] S. Ramakrishnan, M. Delpisheh, C. Convery, D. Niblett, M. Vinothkannan, and M. Mamlouk, "Offshore green hydrogen production from wind energy: Critical review and perspective," Renewable and Sustainable Energy Reviews, vol. 195, p. 114320, May 2024, doi: 10.1016/j.rser.2024.114320.



Report Outline

Related Research » Key challenges and scientific issues

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

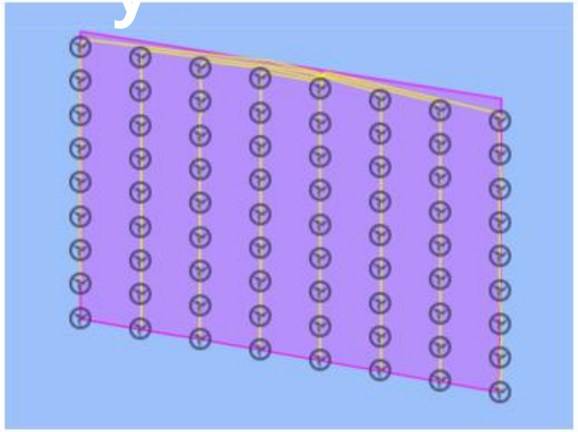
More products (economy)
↓
Reduce levelized cost of hydrogen (LCOH)
↓
Dynamic electrolysis characteristics

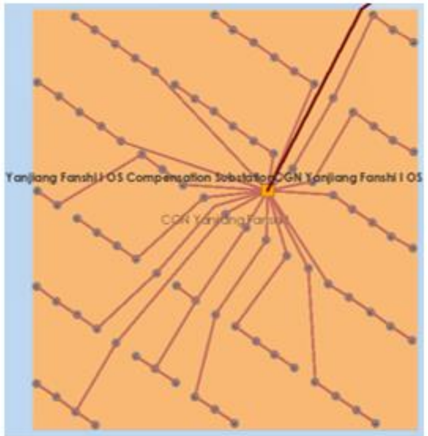
$$
\begin{aligned}
&\min F(x) \\
&\text{s.t. } G(x) \le 0 \\
&x \in D
\end{aligned}
$$

Key Scientific Issues: Modeling and solving Complex Combinatorial Optimization problems

Key issue

The requirements of OWF regular layout, appropriate grid specifications, and refinement wake effect.



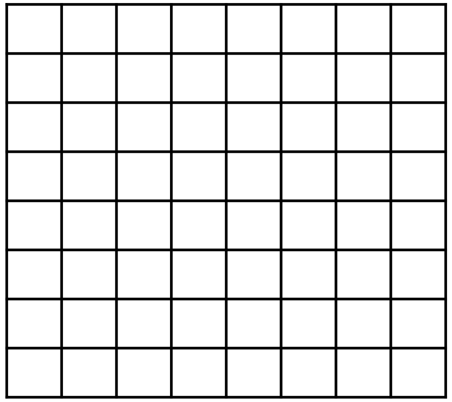


OWFs in Europe(Left)and China Yangjiang (right)

Regular layout of OWF

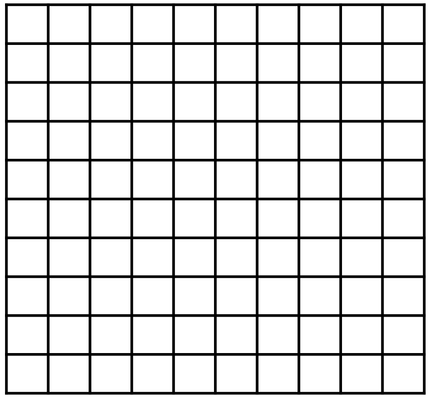
- **Necessity**: 1) reducing the visual impact of nearshore OWF and enhancing the aesthetic appeal of OWFs; 2) lowering the construction costs of infrastructure; 3) facilitating O&M activities; 4) benefiting search and rescue operations
- **Constraints**: 1) Number of WTs per row for 0 or n; 2) The distance between adjacent WTs is the same

8×8 Grid



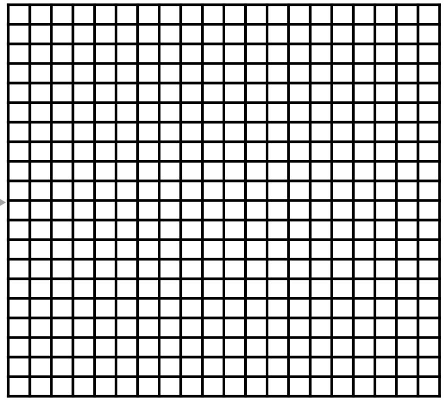
64 0-1variable
15120 Continuous variables
18144 Constraints

10×10 Grid

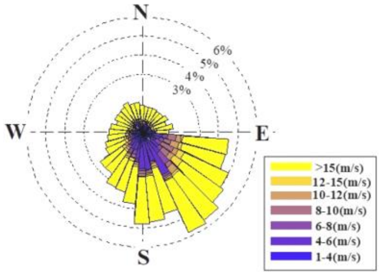


10 0-1variable
18000 Continuous variables
21600 Constraints

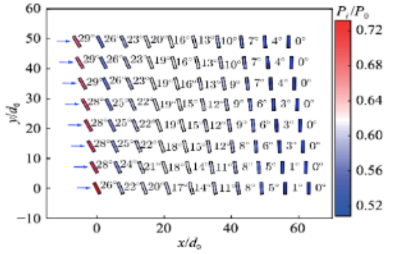
20×20 Grid



400 0-1variable
72000 Continuous variables
86400 Constraints

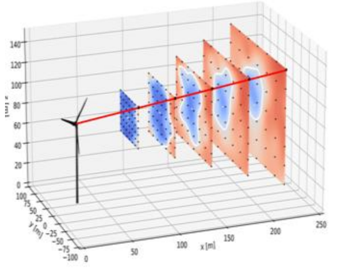


Wind Rose



Wake quantification index

Depicting multi wind scenes based on wind rose diagram



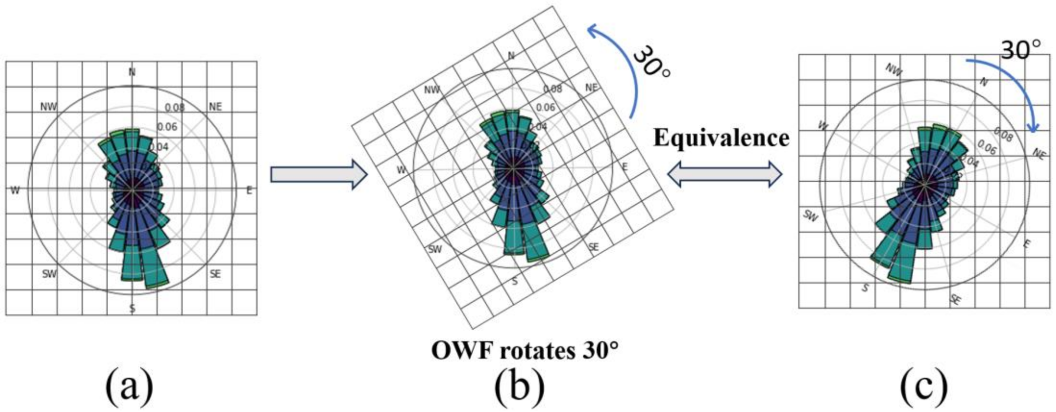
Ideas

Meshing WT layout, introducing rotating coordinates approach;

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

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

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

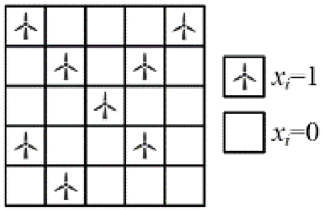
$$x_i + x_j \le 1 \quad \forall(i,j)\in$$

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

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

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

Initial layout plan

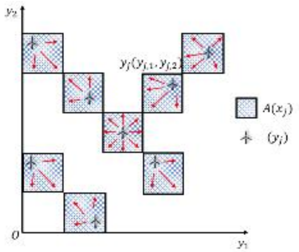


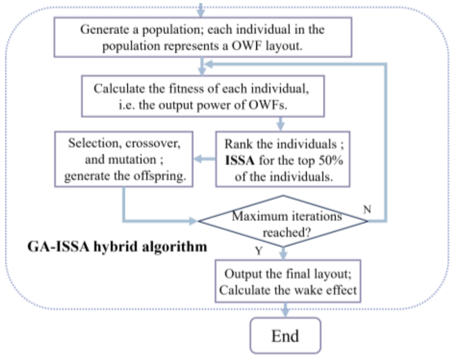
High-quality initial feasible solution

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

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

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

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

2.Further optimization of WT coordinates

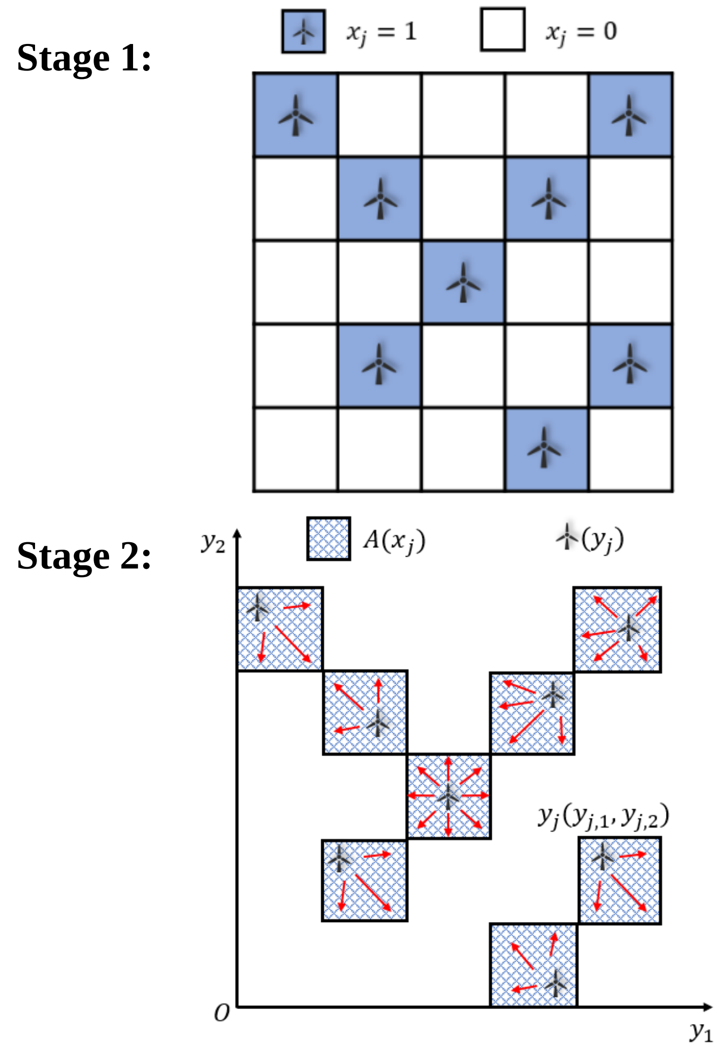
$$\max \sum_{n\in N}\sum_{j\in M}\pi^n P_j^n\left(\boxed{y}, v_j^n\right)$$

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

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

$$(y_{i,1} - y_{j,1})^2 + (y_{i,2} - y_{j,2})^2 \le D_{\min}^2 \quad \forall i,j\in M$$ **Minimum safety distance constraint**

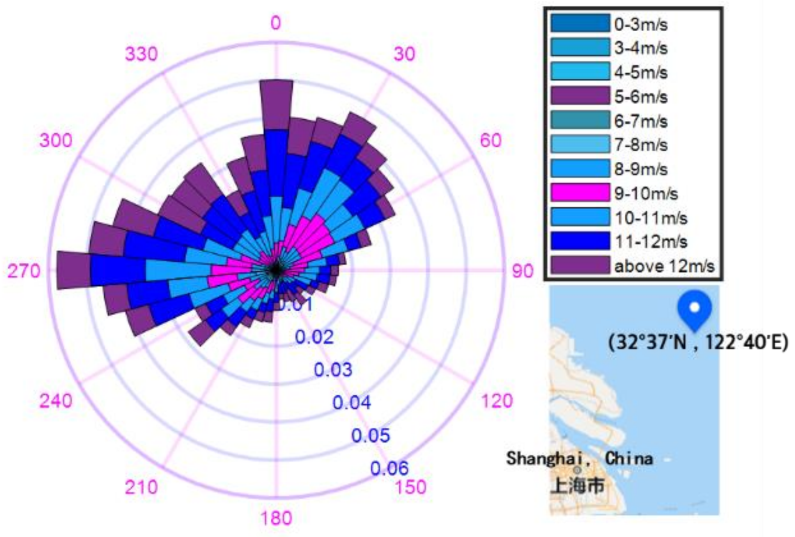
- Schematic diagram



B. Lu, X. Shen*, et al , " Offshore Wind Farm Micro-siting based on Two-Phase Hybrid Optimization ", in Applied Energy, 2025.

Two-stage optimization model for micro-sitting

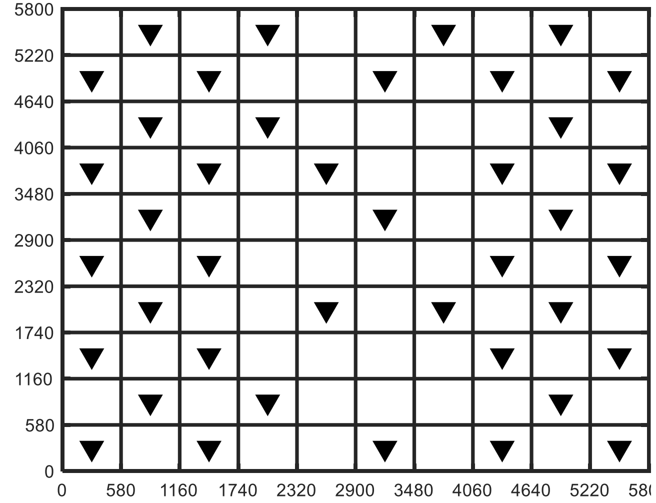
- **Case studies**



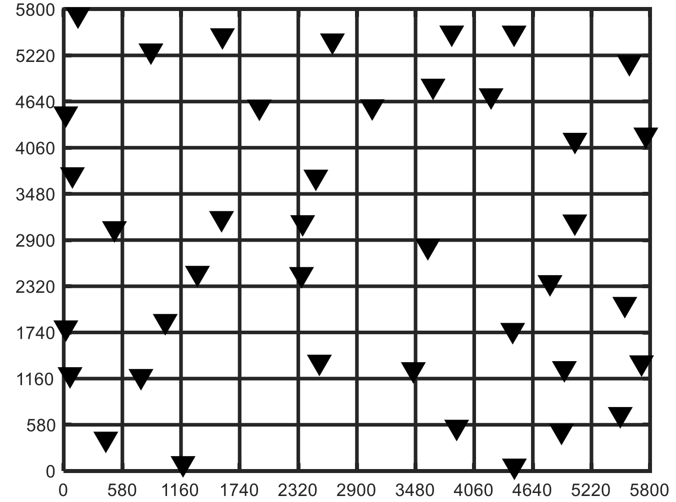
Jiangsu **200MW** OWF **micro-sitting**

- 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)

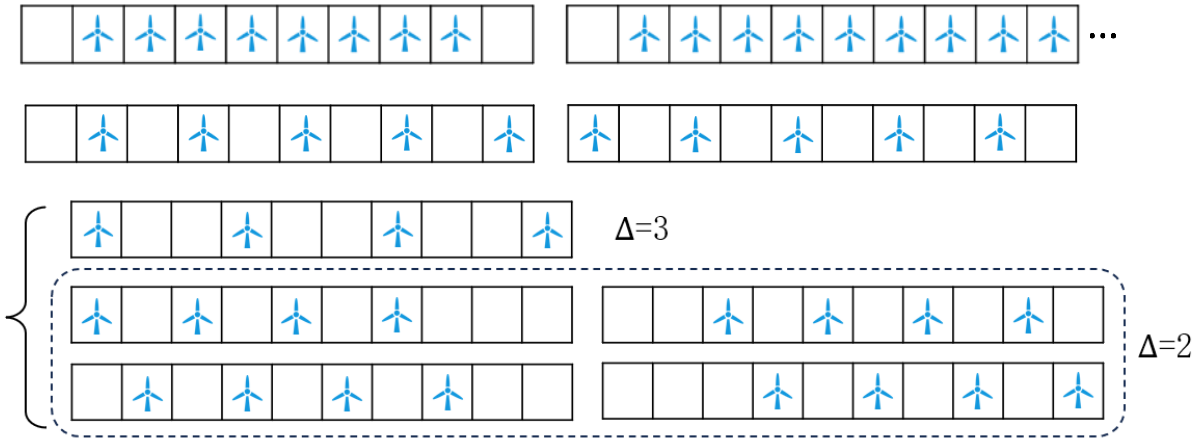
➢ Micro-sitting model for WTs considering regular layout

- 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

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

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

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

Regular layout constraints

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

- **Phase 2 Continuous model**

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

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

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

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

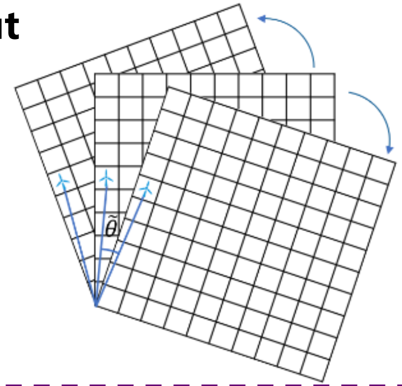
Rotation Constraint

$$\begin{cases} x_{i,1} = x_{i,1}\cos\theta - x_{i,2}\sin\theta & \forall i \in I \\ x_{i,2} = x_{i,1}\sin\theta + x_{i,2}\cos\theta & \forall i \in I \end{cases}$$

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

$$\begin{cases} x_{j,1}^k = x_{i,1}^1 + (k-1)\chi & \forall i,j \in \bar{I} \ \ \forall k \in [1,y] \\ x_{j,2}^k = x_{i,2}^1 & \forall i,j \in \bar{I} \ \ \forall k \in [1,y] \end{cases}$$

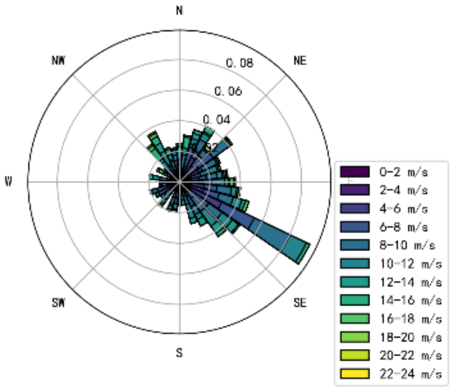
Regular layout constraints



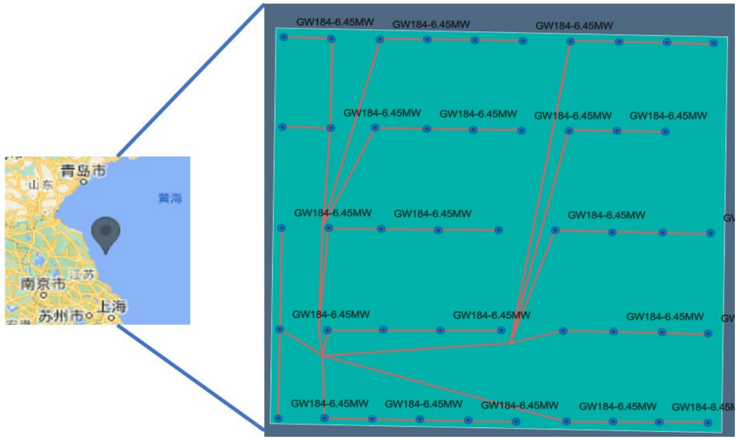
Zehai Huang, **X. Shen***, etc., Two-Phase Micro-siting for Offshore Wind Farms with Regular Layout, submitted to IEEE Trans. on Sustainable Energy, R1

➢ Micro-sitting model for WTs considering regular layout

- Actual Cases

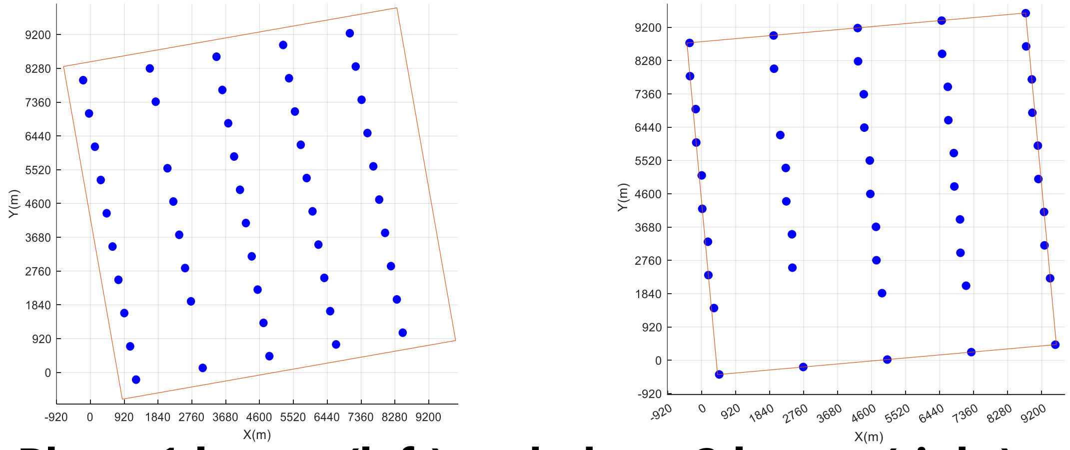


Actual wind rose



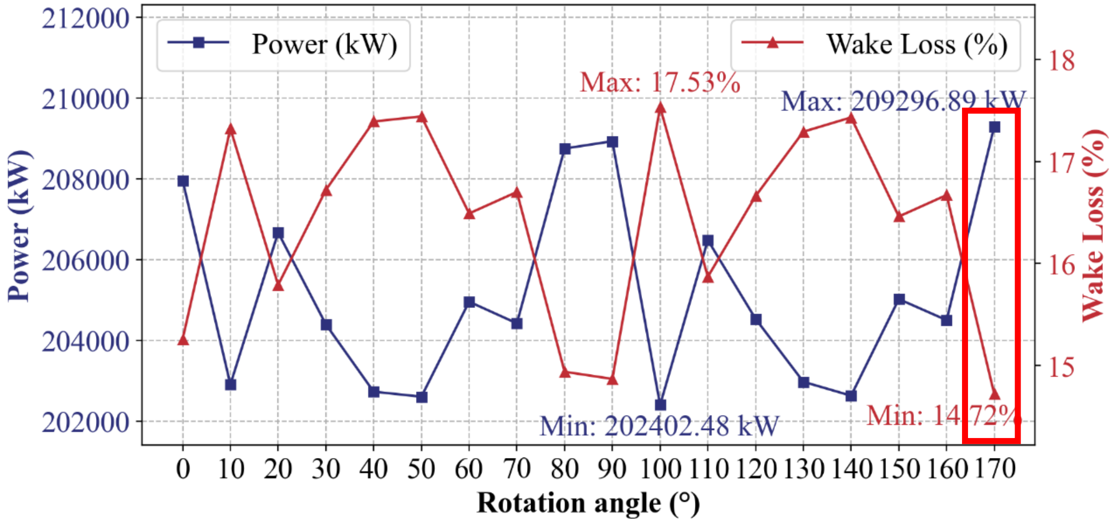
Jiangsu Dafeng H4 OWF

- 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

Related Research 2 » ECS planning

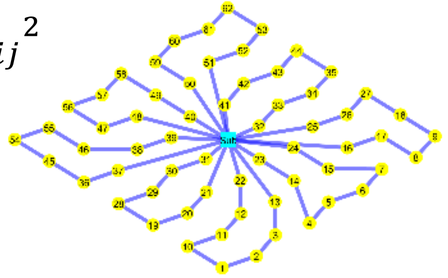
Key point

How to consider complex objectives/constraints such as reliability for optimizing large-scale OWF ECS?

Improved CVRP-based ECS planning

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

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

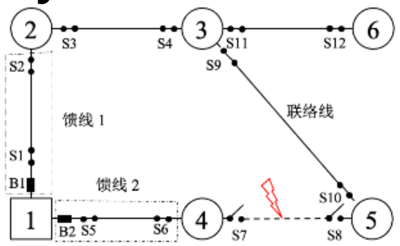


ECS planning results

ECS planning with reliability constraints

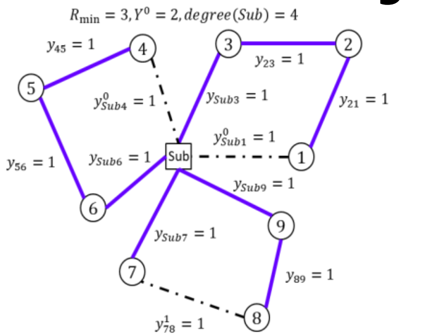
$$\min C_{cap} \sum_{ij\in\Psi_B} d_{ij}l_{ij} + \omega EEND$$

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

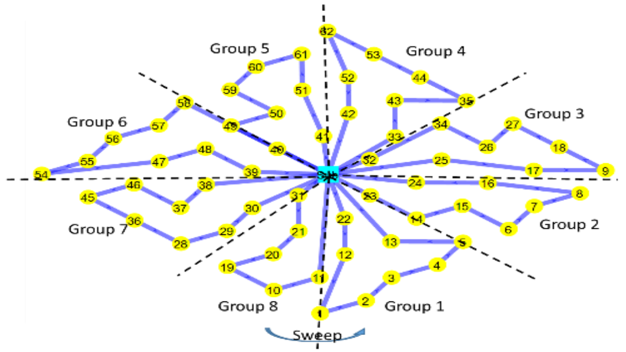


Post-failure network reconstruction modeling

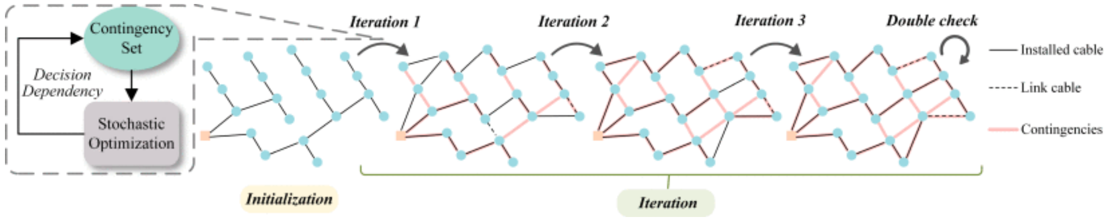
Accelerated solving algorithm of ECS planning



Projection cut set model nether improvements



Initial feasible solution search



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.

Related Research 2 » Ring 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**

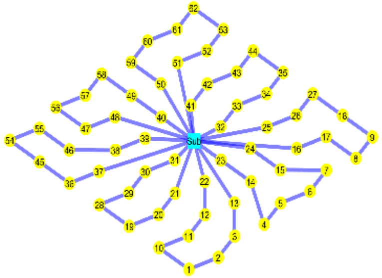
Power network expansion planning model

Incorporating constraints such as **DC power balance**

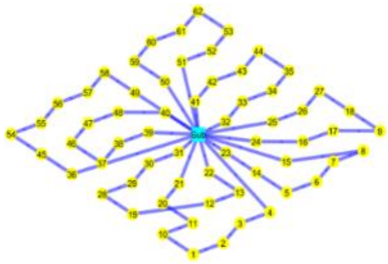
Using approximate methods to value the **network loss**

k-degree centrality tree (k-DCT) model

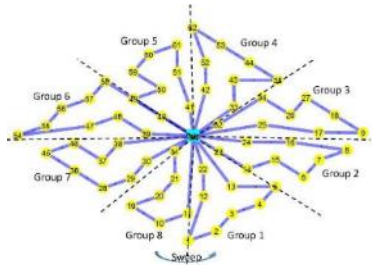
The k-DCT model is used to solve the mTSP, providing a lower bound for CVRP and not affecting the feasibility



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**)

Shen X, Wu Q, Zhang H, et al. Optimal planning for electrical collector system of offshore wind farm with double-sided ring topology. IEEE Transactions on Sustainable Energy, 2023. (Patent and PCT)

- **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.

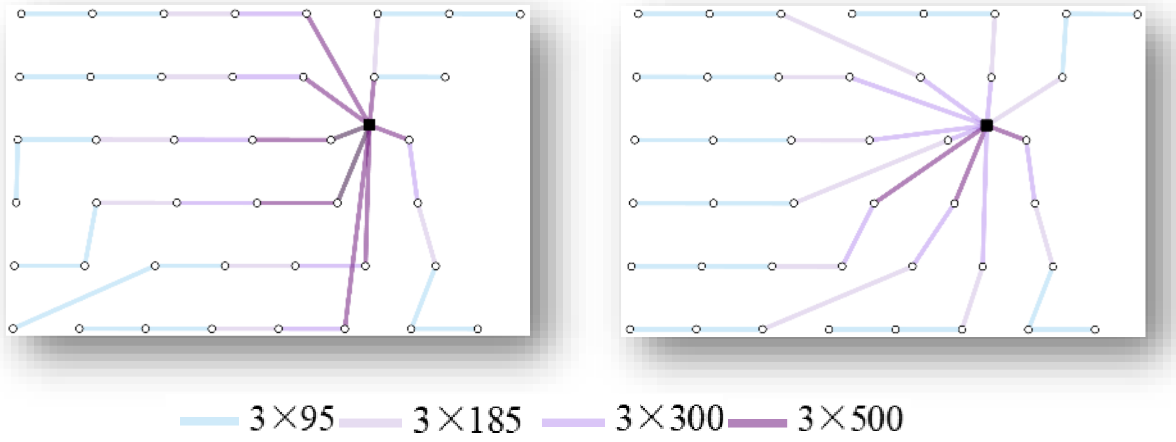
$$\min F^{OW}(x^l, y)$$
$$\text{s.t. } H^{OW}(x^l, y) \geq 0$$
$$x^l \in D$$
$$G^{OW} = (E^{OW}, V^{OW})$$

$x^l \in \{0,1\}^{n\times n\times k}$,

$n = |V^{OW}|$: Number of WTs

k: Type of cables

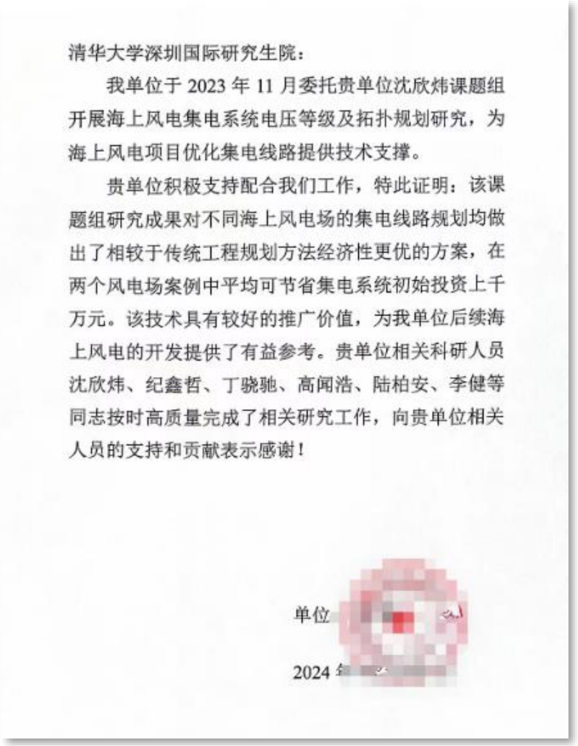
Results for ECS topology and cable type selection



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, submitted to AEPS, R2.

Related Research 2 ❯❯ ECS planning with mixed topology

- **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

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

Cable investment cost — Wind curtailment cost due to contingencies

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

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

- **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:

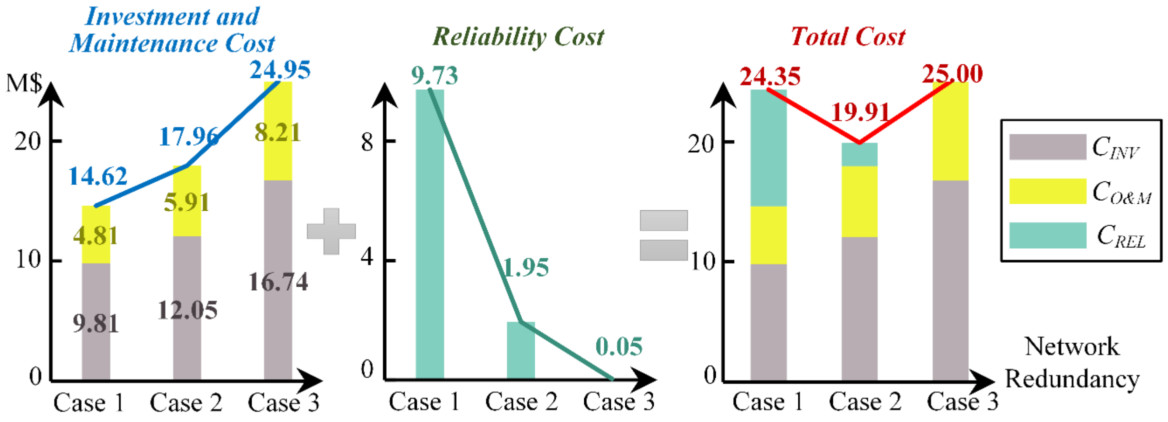
while $Ind == 0$ **do**
  $\tilde{\Upsilon} = \tilde{\Upsilon} \cup \hat{\Upsilon}$;
  Apply BD strategy to solve $(\hat{x}, \hat{y}^{\upsilon,\omega}) = \arg\min_{x, y^{\upsilon,\omega}} \tilde{\mathcal{P}}_{\tilde{\Upsilon},\Omega}$ to $\epsilon \le \epsilon_0$ with warm-start point x_{ws};
  $\hat{\Upsilon}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

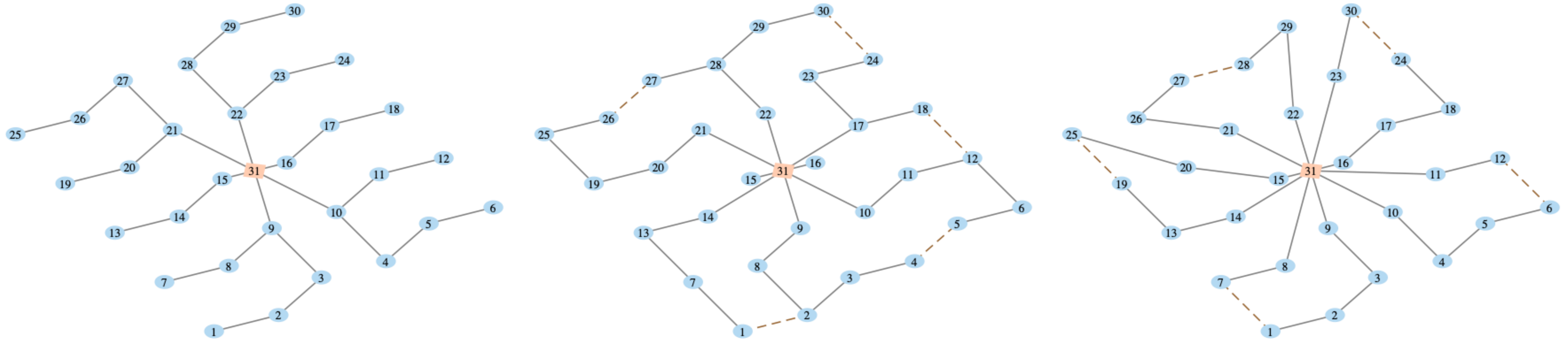
Xiaochi Ding, X. Shen*, et al, "Reliability-Based Planning of Cable Layout for Offshore Wind Farm Electrical Collector System Considering Post-Fault Network Reconfiguration",in IEEE Trans. on Sustainable Energy, 2024.

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

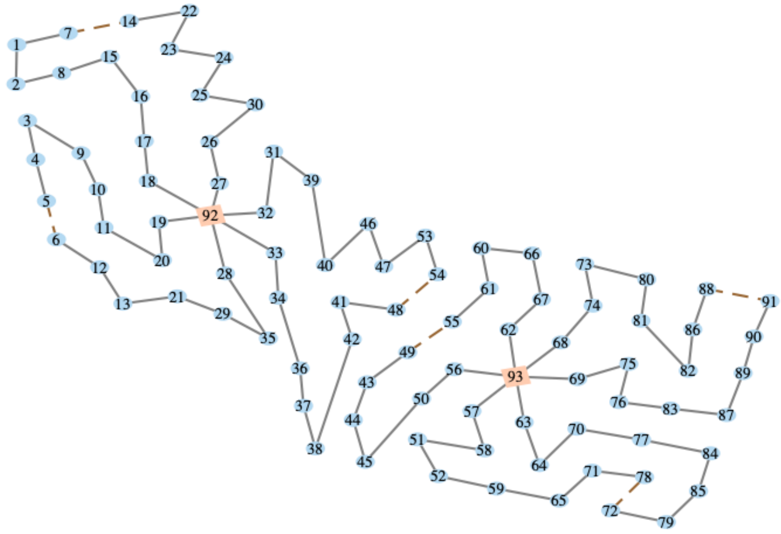
Related Research 2 ❯❯ ECS planning with mixed topology

Case Study-91 WTs Case (RaceBank OWF)

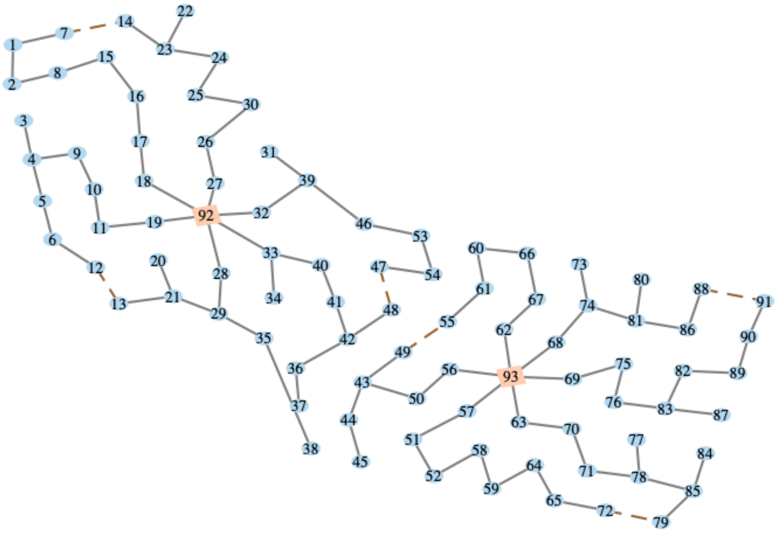
Case 4: ECS planning with two-phase CWS algorithm;
Case 5: Proposed ECS planning without offshore substation coordination;
Case 6: Proposed ECS planning with offshore substation coordination.

TABLE I
RACE BANK OWF ECS PLANNING RESULTS

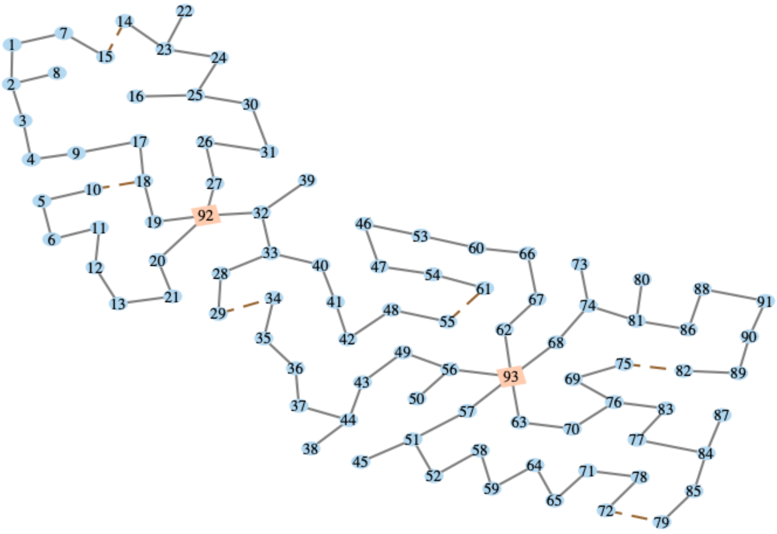
	Case 4 [24]	Case 5	Case 6
$C_{INV}(M\$)$	42.86	40.27	38.82
$C_{O\&M}(M\$)$	21.03	19.76	19.04
$C_{REL}(M\$)$	0.13	1.41	2.91
Total cost $(M\$)$	64.02	61.44	60.77



(a) Case 4: Sweep + CWS planning



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

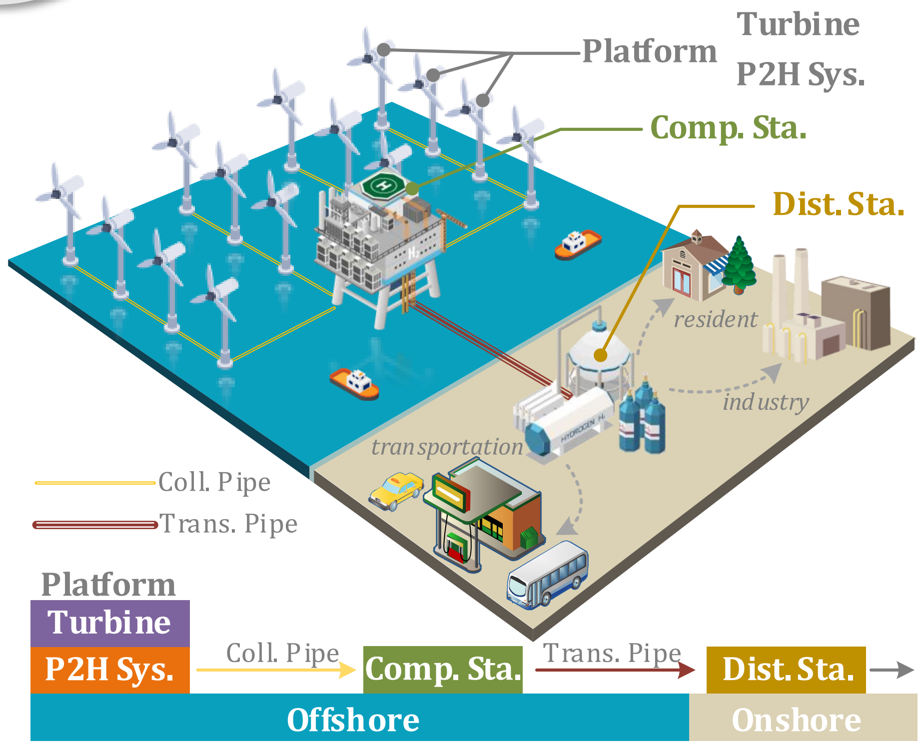


(c) Case 6: Proposed ECS planning with OSS coordination

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.

Key issue

How can the cost of hydrogen production from offshore wind power be further reduced through optimization means at the current level of technology?



OWPHP schematic diagram

- **Hydrogen Production**: A series of platforms are positioned in the sea to harness wind energy and convert it to electricity, which is then transformed into hydrogen through P2H system.
- **Hydrogen Transmission**: The hydrogen is transported through collection pipelines to the compression station for short-term storage. Then, it is transmitted ashore via transmission pipelines.
- **Hydrogen Usage**: Upon reaching the onshore distribution station, it can be further processed, compressed, and prepared 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**

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

Equivalent annual cost (EAC)

Annual hydrogen production (AHP)

Platform location/devices capacity

$$\begin{aligned}
AHP &= \mathbb{E}[H_k^{\mathrm{P2H}}(\mathbb{X}^*, \mathbb{Y}^*, \mathbb{Q}^{\mathrm{P2H}*})] \\
EAC &= EAC_{\mathrm{INV}}(\mathbb{Q}^{\mathrm{P2H}}) + EAC_{\mathrm{OM}}(\mathbb{Q}^{\mathrm{P2H}}) + EAC_{\mathrm{TAX}}(\mathbb{Q}^{\mathrm{P2H}}) \\
EAC_{\mathrm{INV}} &= \sum_{i\in N}(R_{\mathrm{A}}^{\mathrm{P2H}} c_{\mathrm{INV}}^{\mathrm{P2H}} Q_i^{\mathrm{P2H}} + R_{\mathrm{A}}^{\mathrm{WT}} c_{\mathrm{INV}}^{\mathrm{WT}} P_{\mathrm{MAX}}^{\mathrm{WT}}) \\
EAC_{\mathrm{OM}} &= \sum_{i\in N}(c_{\mathrm{OM}}^{\mathrm{P2H}} Q_i^{\mathrm{P2H}} + c_{\mathrm{OM}}^{\mathrm{WT}} P_{\mathrm{MAX}}^{\mathrm{WT}}) \\
EAC_{\mathrm{TAX}} &= c_{\mathrm{TAX}}(c_{\mathrm{H}} AHP - AC_{\mathrm{OM}})
\end{aligned}$$

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

- **Constraints**

$$\begin{aligned}
&\text{s.t.:} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq 5D, \quad \forall i, j \in N \\
&x_{\mathrm{MIN}} \leq x_i \leq x_{\mathrm{MAX}}, \quad \forall i \in N \\
&y_{\mathrm{MIN}} \leq y_i \leq y_{\mathrm{MAX}}, \quad \forall i \in N \\
&0 \leq Q_i^{\mathrm{P2H}} \leq P_{\mathrm{MAX}}^{\mathrm{WT}}, \quad \forall i \in N
\end{aligned}$$

- Platform distance
- OWF boundary
- Devices capacity

■ Second-stage optimization model

- **Objective: AHP**

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

- **Constraints**

$$\begin{aligned}
&\text{s.t.:} \ \gamma_{\mathrm{MIN}} Q_i^{\mathrm{P2H}} \leq I_{k,i}^{\mathrm{P2H}} \leq \gamma_{\mathrm{MAX}} Q_i^{\mathrm{P2H}}, \quad \forall k \in K, \forall i \in N \\
&P_{k,i}^{\mathrm{P2H}} \leq Q_i^{\mathrm{P2H}}, \quad \forall k \in K, \forall i \in N
\end{aligned}$$

- Operation current constraint
- System capacity constraint

$$\begin{aligned}
P_i^{\mathrm{WT}} &\geq P_i^{\mathrm{P2H}} = P_i^{\mathrm{CON}} + P_i^{\mathrm{DES}} + P_i^{\mathrm{ELE}}, \quad \forall i \in N \\
I_i^{\mathrm{P2H}} &= f(P_i^{\mathrm{P2H}}), \quad \forall i \in N \\
P_i^{\mathrm{CON}} &= \beta_2 (I_i^{\mathrm{P2H}})^2 + \beta_1 I_i^{\mathrm{P2H}} + \beta_0, \quad \forall i \in N \\
P_i^{\mathrm{DES}} &= \psi^{\mathrm{DES}} h_i^{\mathrm{P2H}}, \quad \forall i \in N \\
P_i^{\mathrm{ELE}} &= N^{\mathrm{C}} U_i^{\mathrm{C}} I_i^{\mathrm{P2H}}, \quad \forall i \in N \\
U_i^{\mathrm{C}} &= E + U_i^{\mathrm{O}} + U_i^{\mathrm{ACT}} \\
h_i^{\mathrm{P2H}} &= \frac{N^{\mathrm{C}} I_i^{\mathrm{P2H}} \eta^{\mathrm{F}}}{2F}, \quad \forall i \in N
\end{aligned}$$

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

[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, AEPS, 2024.

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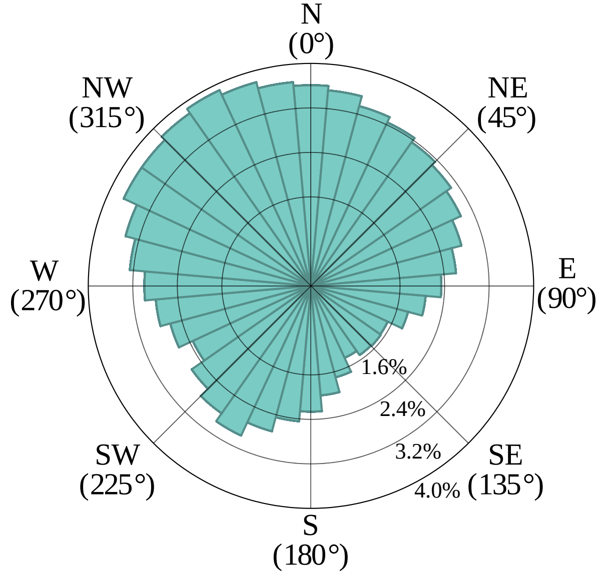
□ Two stage stochastic optimization model for hydrogen production process

□ Case studies:

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



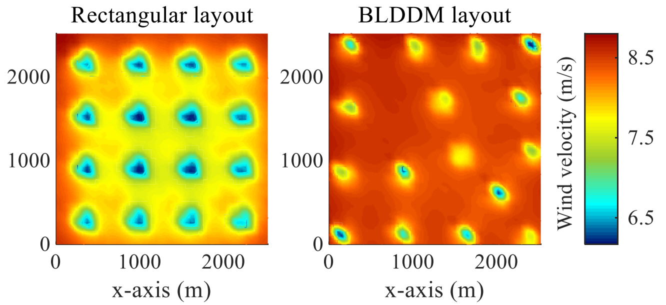
- ✓ The initial layout of the platform adopts **rectangular layout**

□ Platform layouts

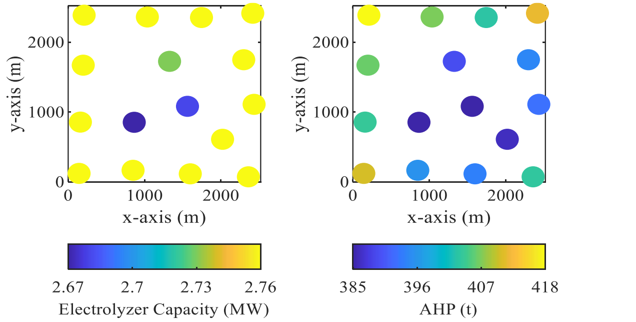
Jointly optimized LCOH : 6.33 €/kg

- ✓ Reduced by 19.67% compared to the engineering scheme (case 1);
- ✓ Reduced by 15.82%/3.21% compared to separately optimization (case 2/3);

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

- ✓ The electrolyzer capacity and AHP meet the principle of "larger values at the edge and smaller values inside" due to different wake effect.

[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:

$$\min_{\boxed{x^{GS},y^{GS}},\boxed{\xi_{i,j}}} \underbrace{C^{TPL}(x^{GS},y^{GS})}_{\text{Transmission pipeline (TPL) cost}} + \underbrace{C^{GPL}(x^{GS},y^{GS},\xi_{i,j})}_{\text{Gathering pipeline (GPL) cost}}$$

Investment decision variables of candidate GPL (binary variables)

Coordinates of gathering station nodes (continuous variables)

Constraints

Gathering station location range constraints

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

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

Spanning tree constraints

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

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

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

$$\xi_{i,j} + \xi_{m,p} \le 1,\ \forall \{i,j\} \times \{m,p\} \ne \varnothing, \{i,j\},\{m,p\} \in L \qquad \sum_{\{i,j\}\in L_{GS}} \xi_{i,j} = Z$$

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

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

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

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

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

Second Phase: Gathering Station Location Refinement

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

[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.

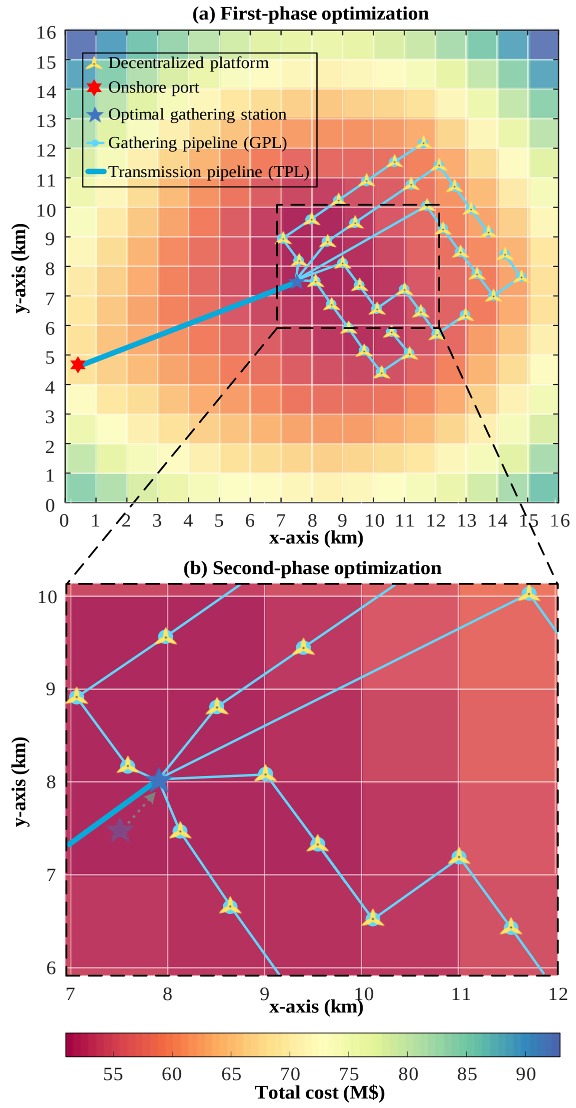
☐ Co-optimization model for pipeline and hydrogen gathering station

- ☐ **Case 1**: Separate optimization for gathering station location and pipeline typology.
- ☐ **Case 2**: First-phase optimization.
- ☐ **Case 3**: Two-phase optimization.

Comparison of performance in different cases

Cases	TPL length/km	GPL length/km	Total cost	
			M$	% over Case 3
1	11.22	37.49	54.78	8.86 %
2	7.78	40.83	51.10	1.55 %
3	8.34	38.73	50.32	/

- ☐ **In Case 1**, the gathering station is positioned at the center of the site, overlooking the benefits of joint optimization. Consequently, the cost is higher compared to Case 2 and 3, with an increase of 8.86% over Case 3.
- ☐ Placing the gathering station at the site edge (in Cases 2 and 3) increases the length of the GPLs, but it also reduces the length of the more expensive TPLs. When these factors are combined, the overall cost is lower.
- ☐ **In Case 2**, the cost is higher than in Case 3 due to the inherent error introduced by the gridding, resulting in a 1.55% increase, which proves the two-phase method is better than the first-phase approach.



[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.
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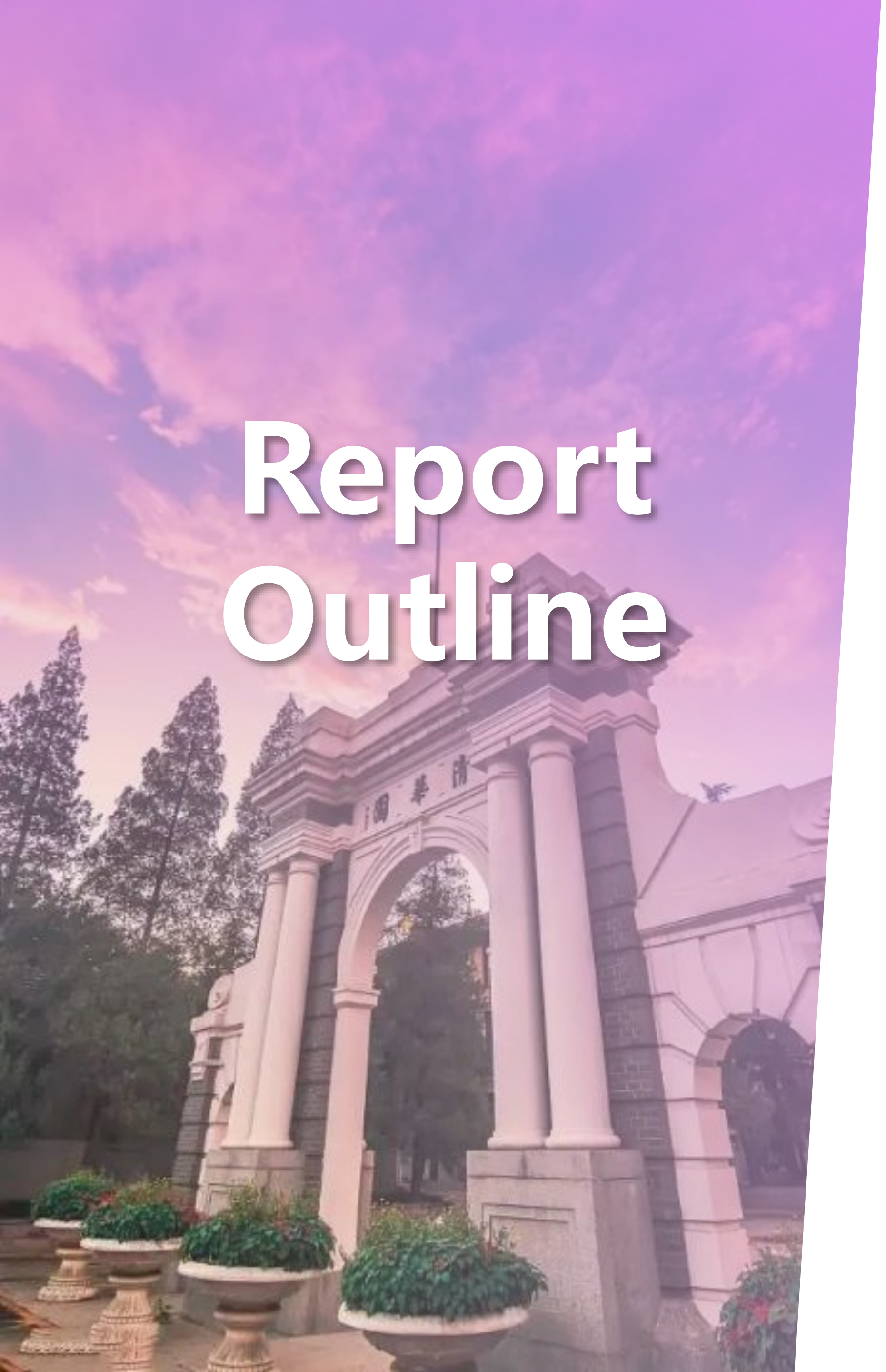
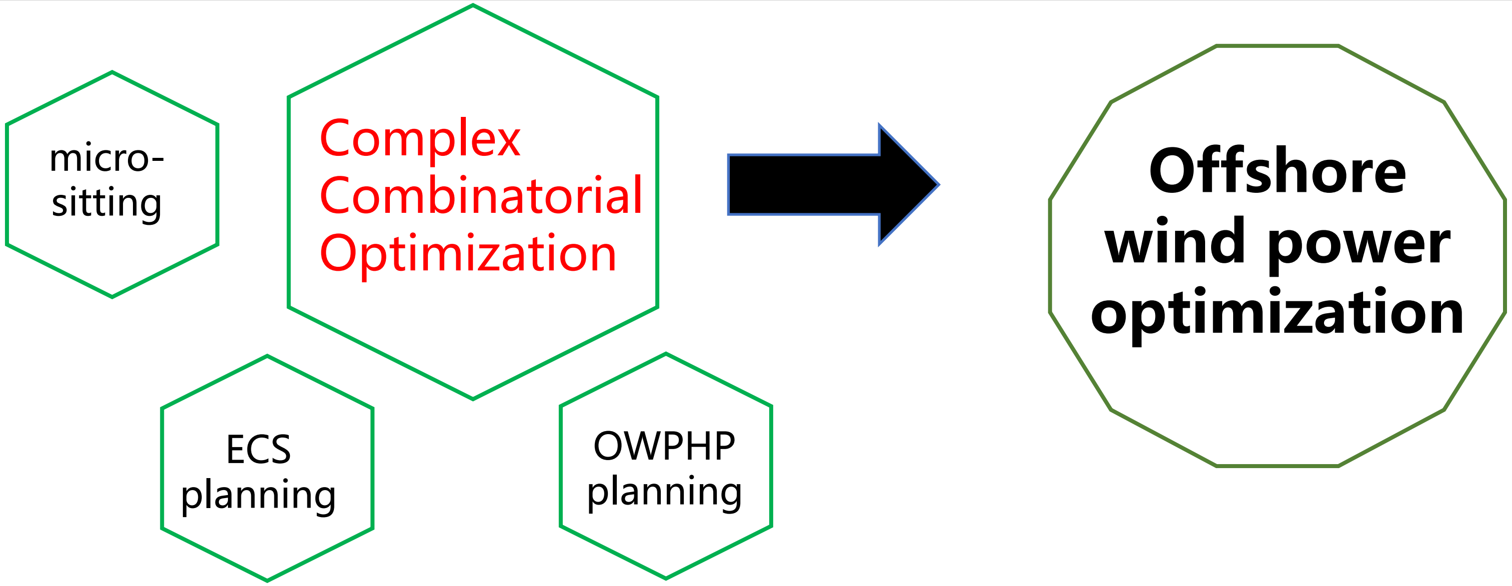


Report Outline

Summary

1. Considering wake effects and regular layout requirements, conduct micro-sitting for OWF WTs could reduce the LCOE.
2. Considering reliability requirements and transmission power balance, proposed ECS planning method could reduce the LCOE.
3. By optimizing different processes of OWPHP, such as hydrogen production, transmission, and usage, LCOH can be reduced.

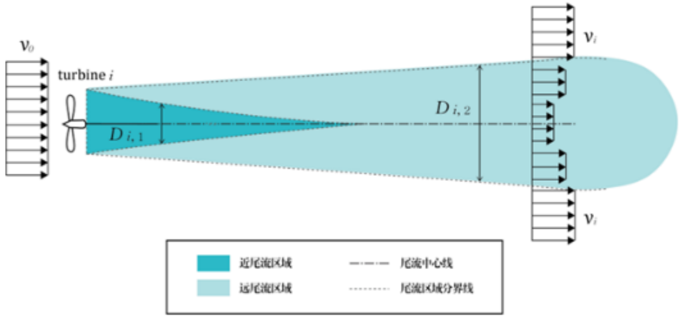


Key scientific issues: Model and solve complex combinatorial optimization problems

Future Outlook——Towards floating, deep sea

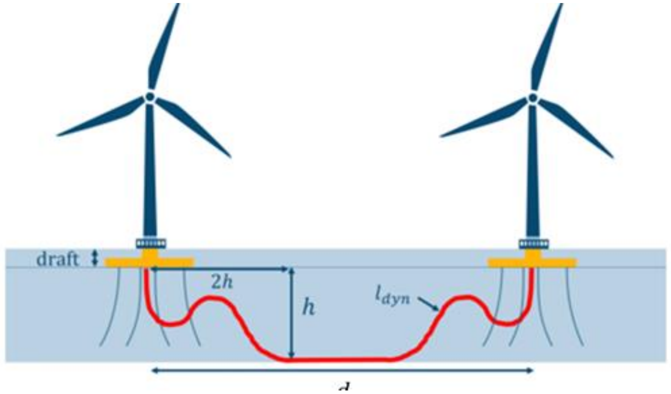
- **☐** The cost of deep-sea fixed infrastructure is growing exponentially.
- **☐** New development trends*:**Floating**+**Dynamic submarine cable**+**Power to X**.

Micro-sitting



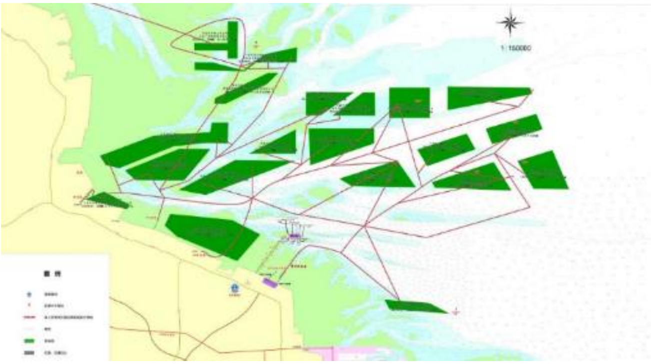
Simulate the displacement of a floating WT under six degrees of freedom, and consider the special near-field/far-field wake.

ECS planning



Dynamic submarine cables have swinging and redundancy, making the potential reliability issues are prominent.

OWPHP planning



Explore processing of OWPHP to obtain hydrogen derivatives, and achieve deep decarbonization of oil and gas platforms through OWPHP.

Related publications/patents

清華大学深圳国际研究生院
Tsinghua Shenzhen International Graduate School

◆ Published/submitted 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] 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.

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

[8] 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.

[9] Yufei 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.

[10] Wenhao Gao, **X. Shen***, etc., Optimization planning of offshore wind power collection system based on large-scale mixed integer programming, submitted to AEPS, R2.

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

In math we trust, in application we trust

Thanks!

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Thanks to NSFC/Guangdong/Excellent Youth Research Fund of Shenzhen!
To Xiaochi (晓驰)、Yunfei (云飞)、Boan (柏安)、
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