

# Wind Farm Siting: Deep Learning-Based Cross-Scale Super-Resolution Modeling



National  
Taiwan  
University  
國立臺灣大學



## Authors

<sup>1</sup> **Jun-Wei Ding**

Ph.D. Student, Dept. of Civil Engineering, National Taiwan University

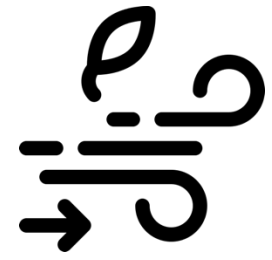
<sup>2</sup> **I-Yun (Lisa) Hsieh**

Associate Professor, Dept. of Civil Engineering, National Taiwan University

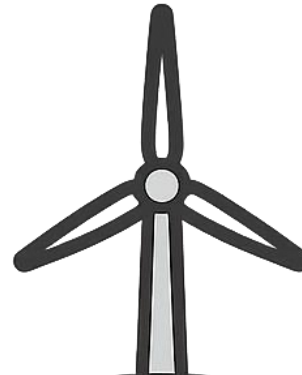
## Date

**Sep. 4. 2025**



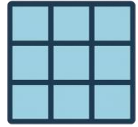


Wind Data



Wind Power





### Reanalysis Data

- Offers temporal consistency & long-term coverage
- ✗ Limited by coarse spatial resolution



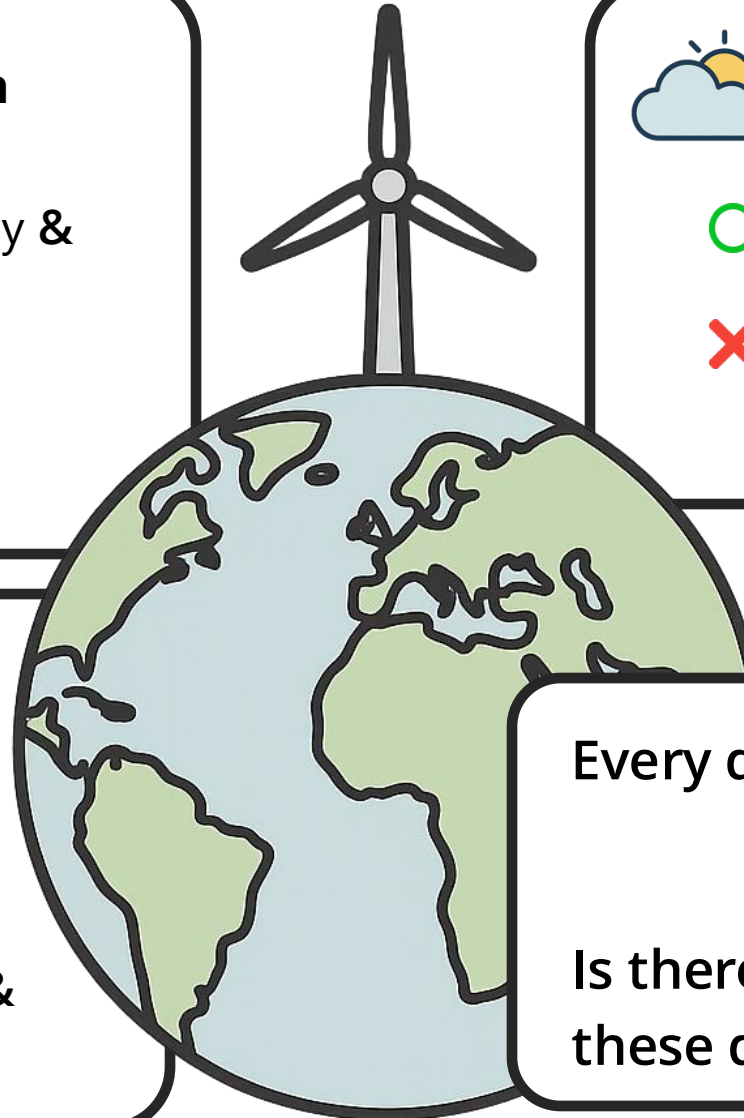
### Numerical Weather Prediction

- Provides high spatial resolution
- ✗ Subject to forecast errors and limited historical accessibility



### Ground Station

- Closest approximation to ground truth
- ✗ Sparse spatial distribution & limited regional coverage



Every dataset has its pros and cons.

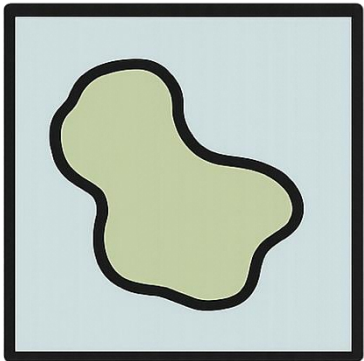


Is there a more effective way to utilize these datasets?

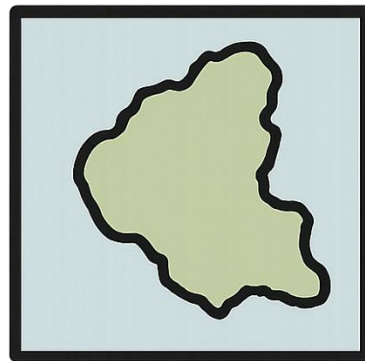


# Research Problem 1

Can we leverage the benefit of distinct data simultaneously ?



Low Resolution (LR)  
Wind Data



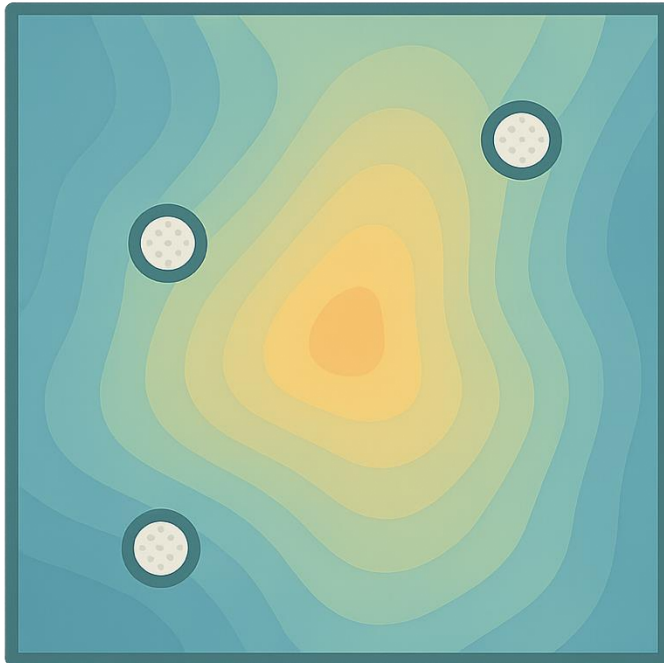
High Resolution (HR)  
Wind Data

- Structural misalignment makes **learning mappings** challenging
- Small-scale features are often **stochastic & nonlinear**



## Research Problem 2

How to evaluate gridded data using Point-based observation?

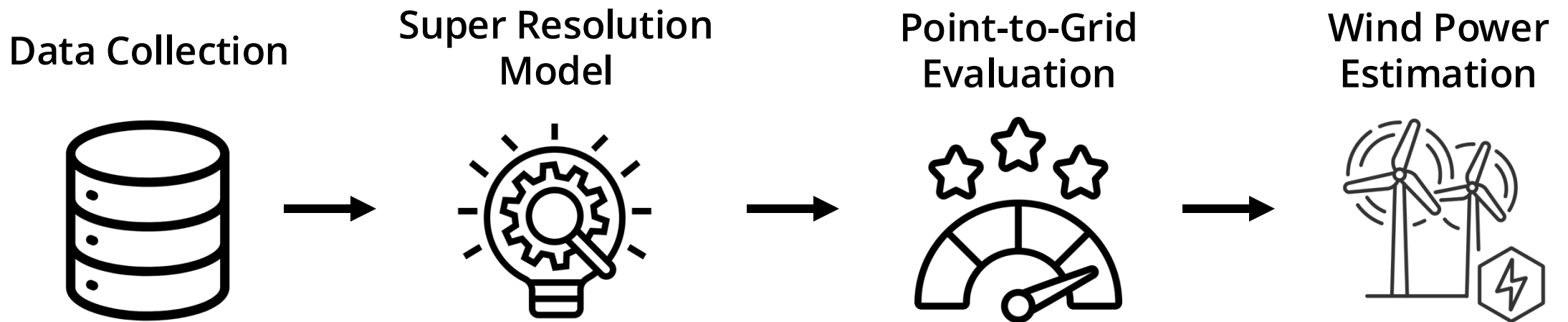


- Points **cannot** represent entire grid cells
  - ✓ **Non-uniform** distribution of observation points
  - ✓ **Insufficient** number of stations
- Kriging-based Point-to-Grid (P2G) method
  - ✓ May distort the actual representativeness of observations due to **smoothing assumption**.



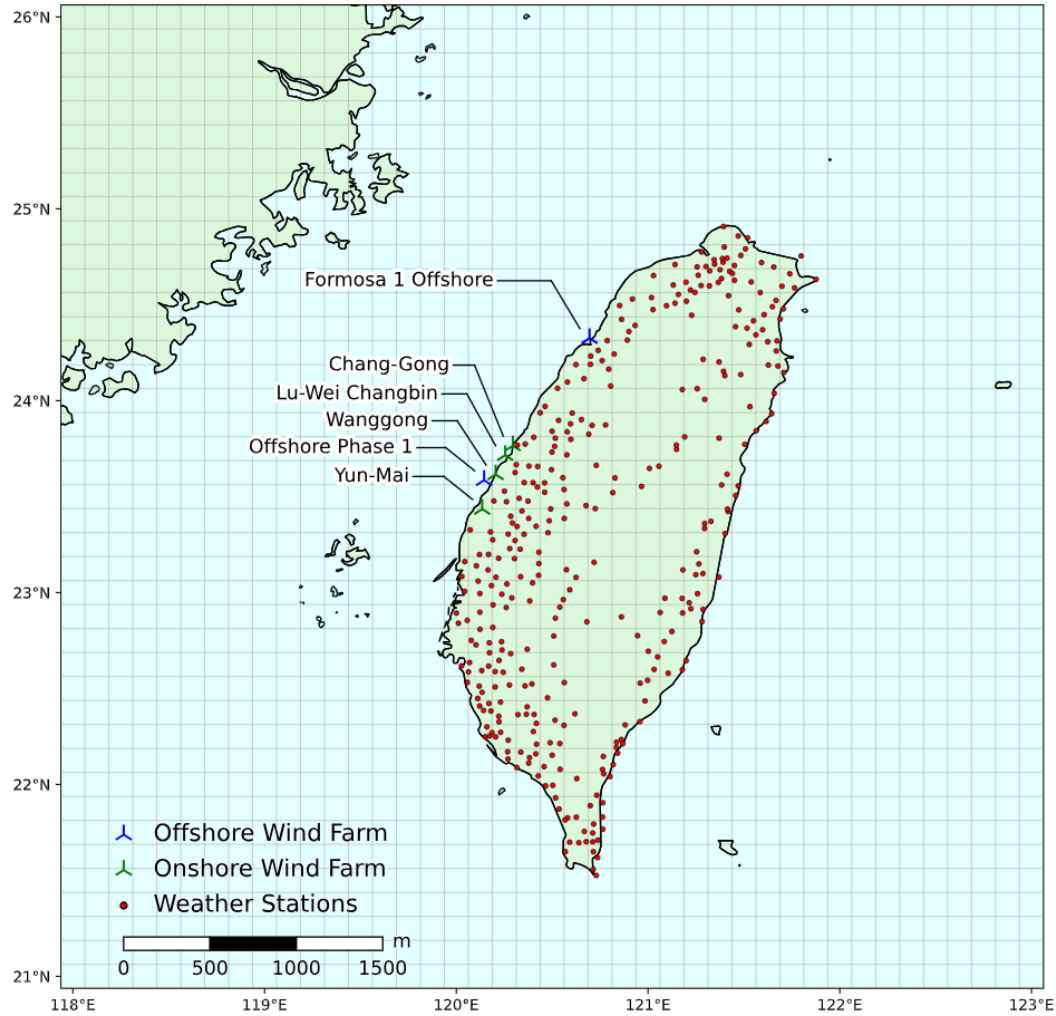
# Research Objective and Workflow

- ✓ Design a **Super Resolution model** to combine diverse datasets, enhancing resolution and accuracy.
- ✓ Introduce a **Point-to-Grid Evaluation Framework** with sparse observations.





# Case Study



📍 Study Area

- ✓ Taiwan
- ✓ 118 - 123°E
- ✓ 21 - 26°N

🕒 Study Period

- ✓ Training: 2022-2023
- ✓ Testing: 2024





# Dataset



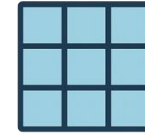
## Numerical Weather Prediction

- ✓ ICON (ICOsahedral Nonhydrostatic)
- ✓ Spatial Resolution: 0.125 °
- ✓ u-, v- wind



## Ground Station Observation

- ✓ Central Weather Administrative
- ✓ 345 ground stations



## Reanalysis Data

- ✓ ERA5 on single level
- ✓ Spatial Resolution: 0.25 °
- ✓ u-, v- wind

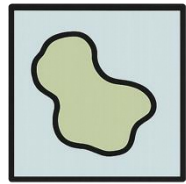


## Wind Power Generation

- ✓ Taipower Company
- ✓ Six Wind Farm

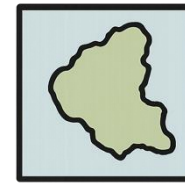


# Super Resolution (SR) Model



Low Resolution Data

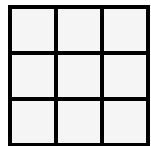
➔ Reliable **large-scale** features



High Resolution Data

➔ Additional **fine-scale** information

## Feature Extraction



Uniform Filter

+

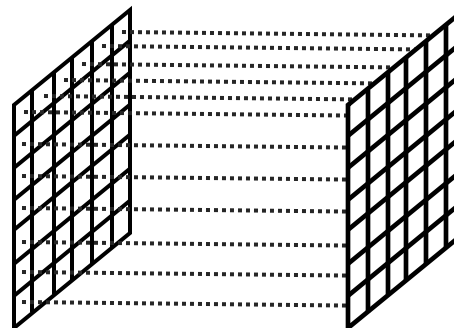


Spectrum Analysis



## Hybrid Training Strategy

Content Loss

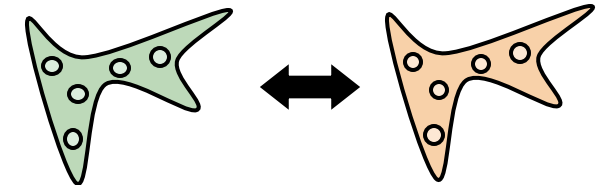


$SR^l$

$LR^l$

+

Adversarial Loss



$SR^h$

$HR^h$



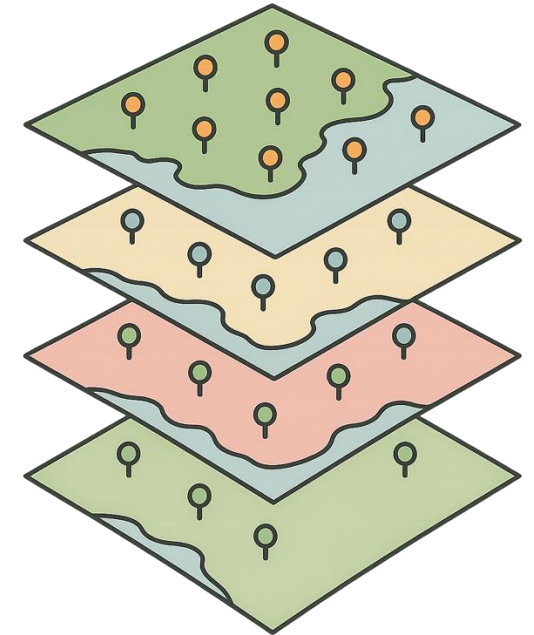
# Point-to-Grid (P2G) Evaluation

Observation Stations are **unevenly distributed**

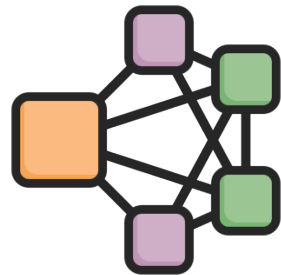
➔ Distance-based clustering is introduced to ensure evaluation is based on **spatially balanced observation groups**.

Point-based observation **cannot** represent the whole grid

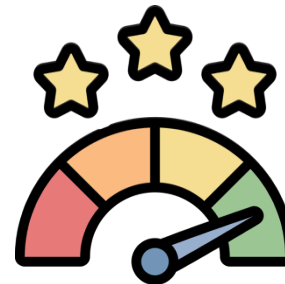
➔ A **broader spatial view** allows point data to better **represent grid-scale information**.



Distance  
Calculation



Clustering



Evaluation



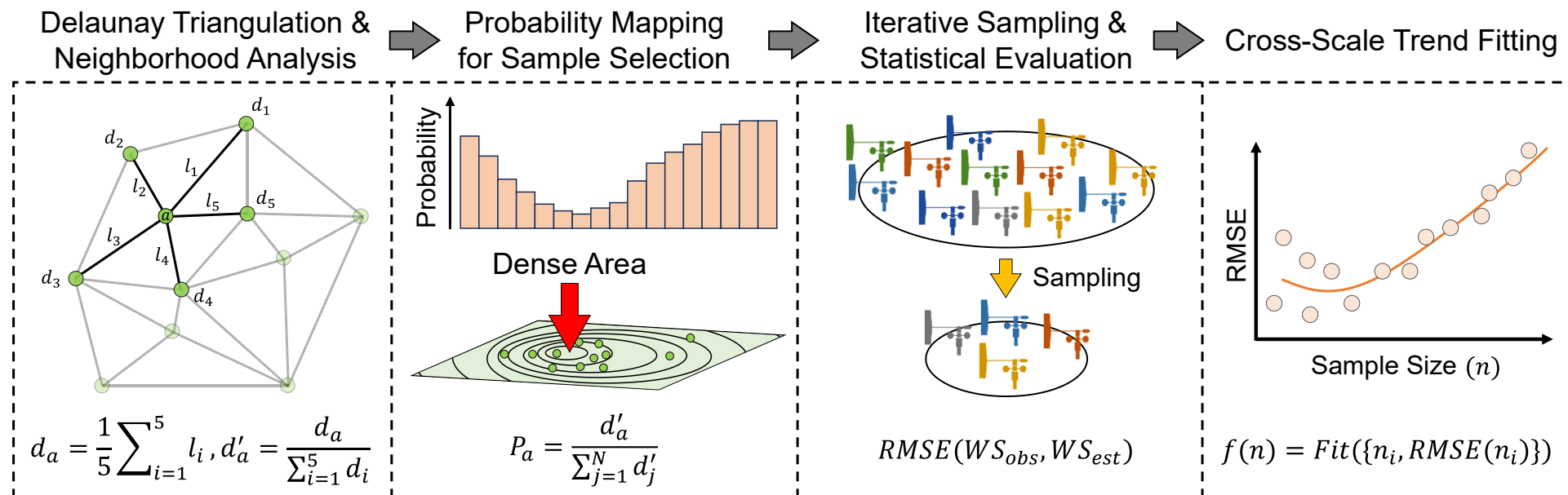
Sensitivity Analysis  
Leave-One-Out  
(LOO)



# Point-to-Grid (P2G) Evaluation

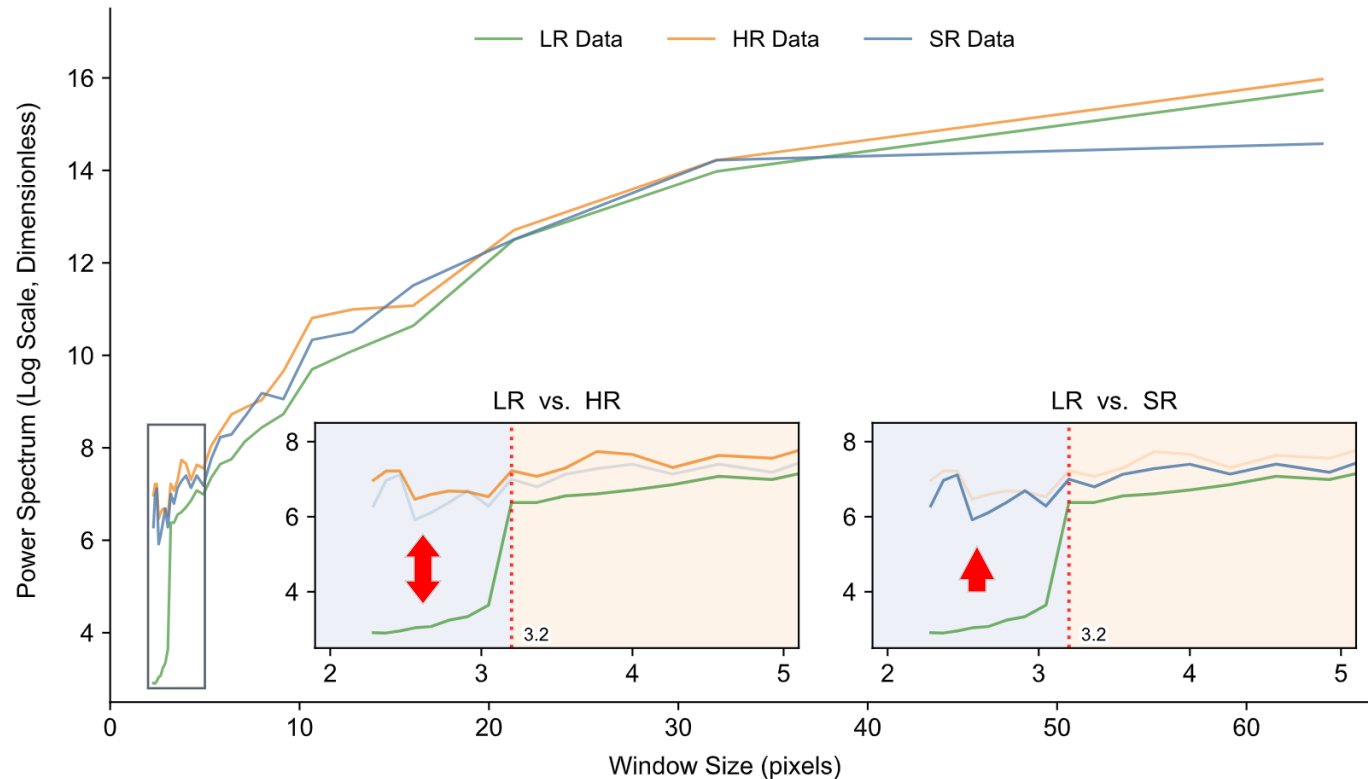
Uncertainty and inter-station variability

- ✓ Monte Carlo-based sampling is used to simulate **multiple spatial scenarios**
- ✓ **Cross-scale regression** is employed to achieve a more robust evaluation





# Spectrum Analysis



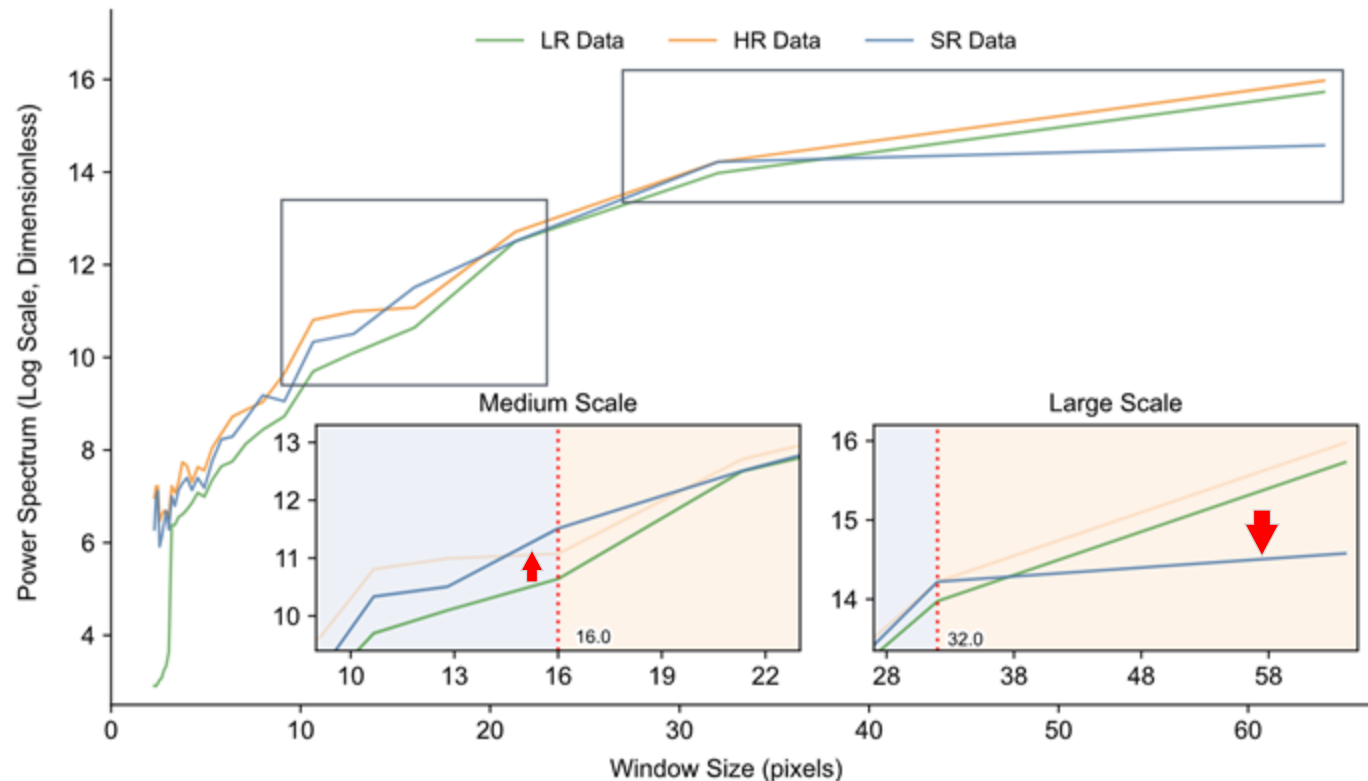
A **significant drop** is observed when the window size is less than 3.2



A window size of 3 is used as the **threshold** to extract the patterns



# Spectrum Analysis



Our SR model not only **fills in high-frequency details**



But also **balancing** both high- and low-frequency features



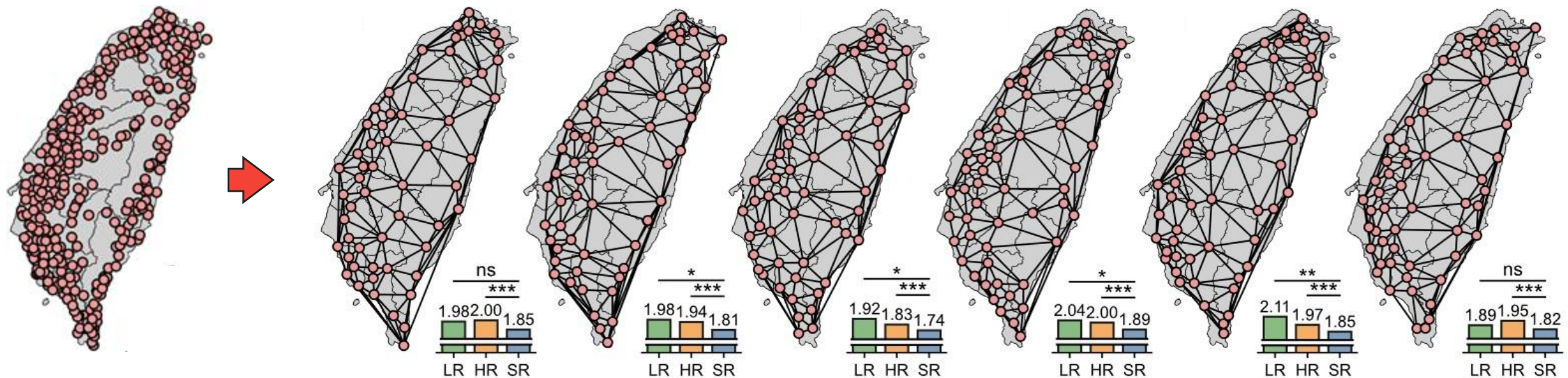
# P2G - Clustering Evaluation

## SR vs. LR

- ✓ Outperforms in **6** clusters
- ✓ Statistically significant in **4** clusters

## SR vs. HR

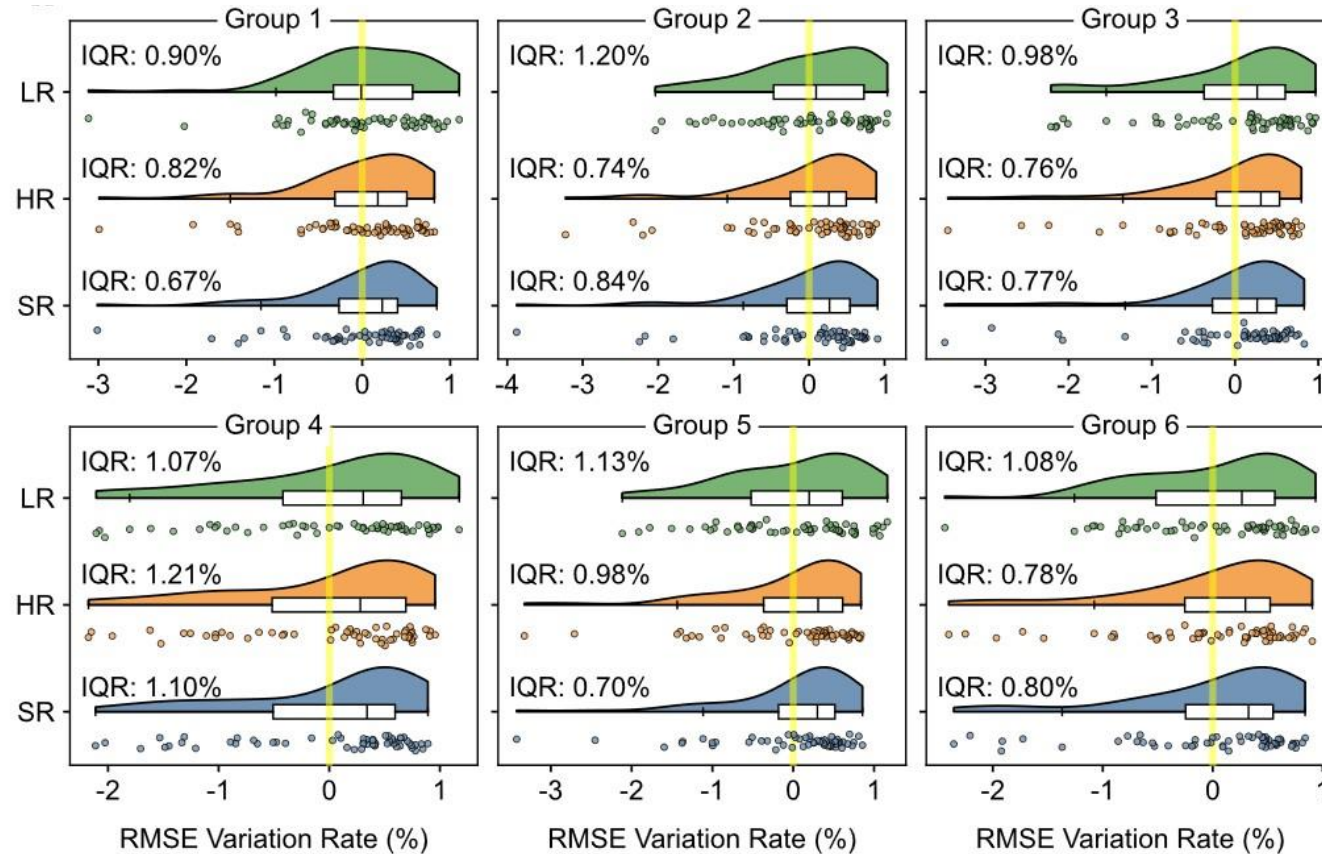
- ✓ Outperforms in **6** clusters
- ✓ **All** differences statistically significant



\*RMSE



# P2G - Sensitivity Analysis



Distribution with **median above zero**

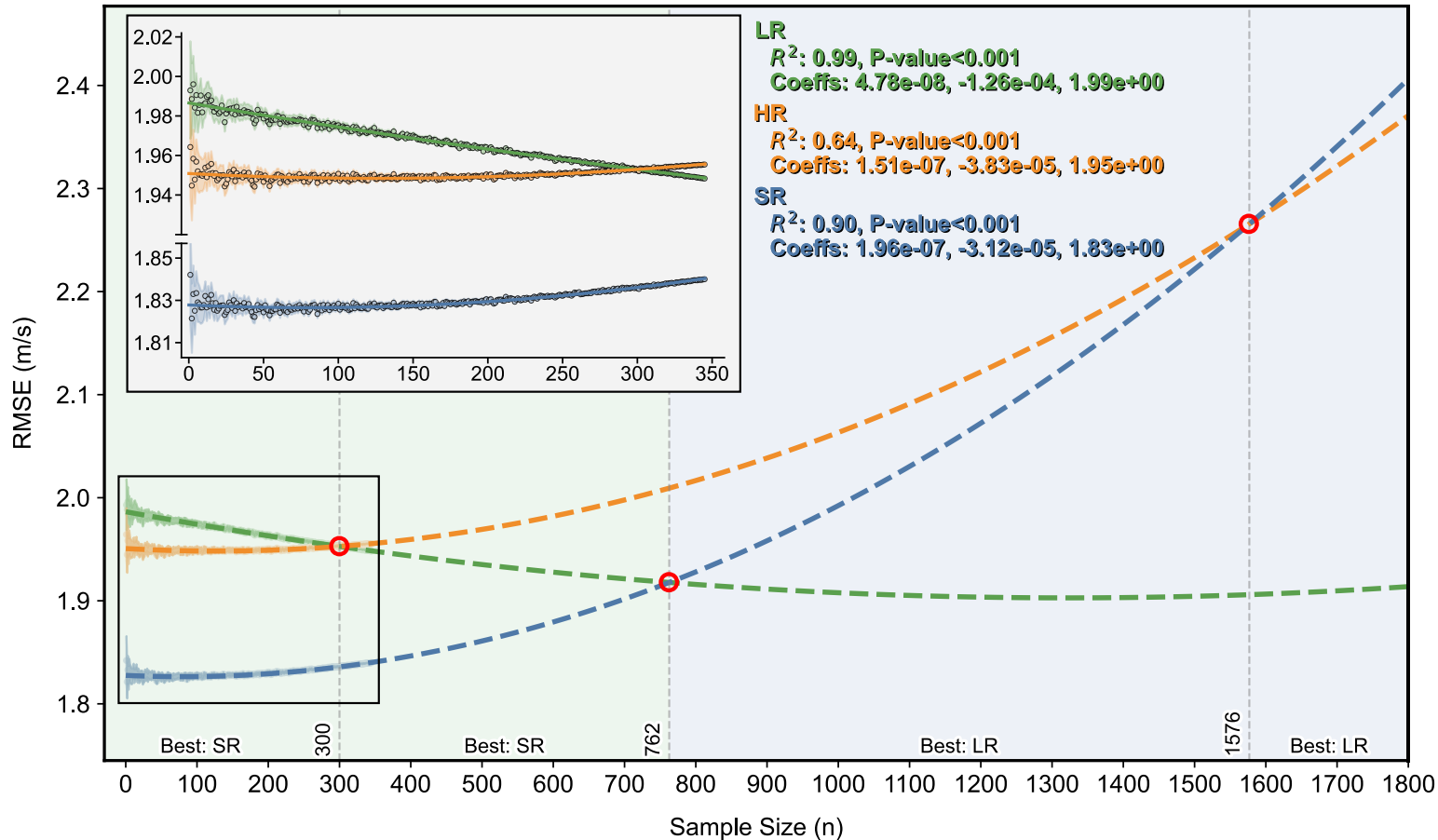
✓ P2G error impact **decreases** with more evaluation points

SR shows **smaller IQR** than LR

✓ **SR reduces uncertainty** compared to LR



# P2G - Cross Spatial Evaluation

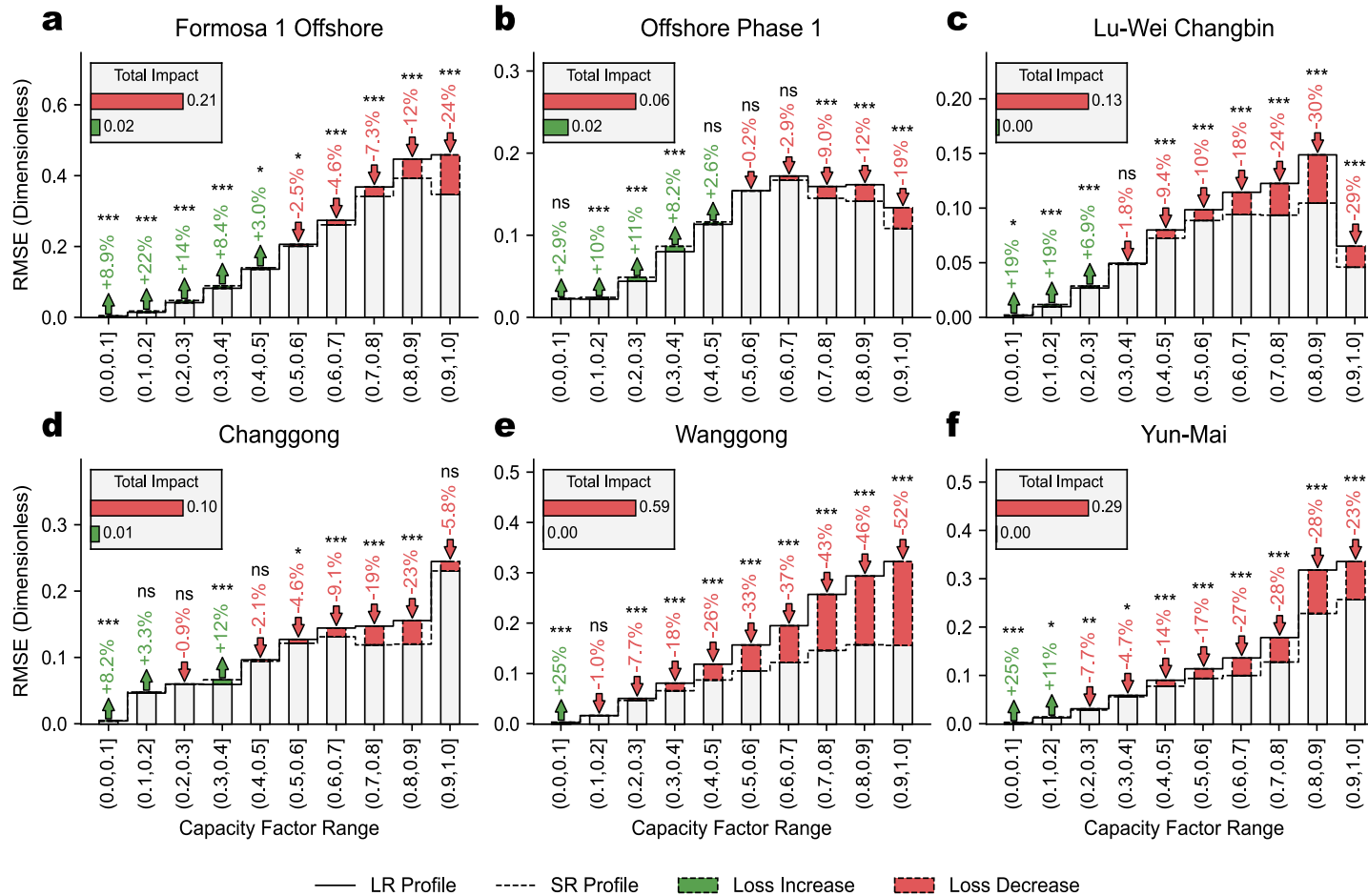


Assume the future stations will follow a **similar spatial distribution** as existing ones.

Coverage	LR	HR	SR
	2	3	
	2	3	
		2	3



# Wind Power Estimation Accuracy



A strategy that trades low-generation accuracy for improved high-generation performance



At most **52%** RMSE improvement



# Conclusion

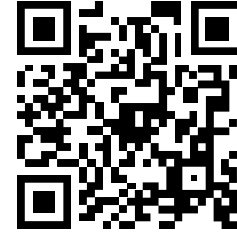
- Can we leverage the benefit of distinct data simultaneously? **YES**
  - ✓ Our SR model can **identify** and **integrate** distinct data patterns from distinct sources, enhances wind power estimation accuracy, achieving up to a **52% improvement**.
- Can the Point-based observation used to evaluate the gridded data? **YES**
  - ✓ The introduced P2G Evaluation Framework shows that the SR model have an **average improvement of 8%** and outperforms others under **twice the area of Taiwan**.



# Jun-Wei Ding

Dept. of Civil Engineering, National Taiwan University

Email: d13521023@ntu.edu.tw

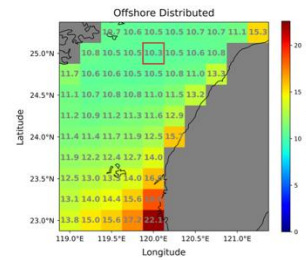


# E3 Center

Energy, Economics & Environment

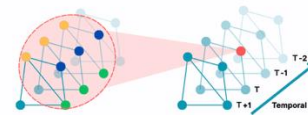


Offshore Distributed Configuration



**Grid**  
Taipower's Grid → Lamps  
System cost: \$USD 144,455

**675**  
tons of CO<sub>2</sub>e



**Solar**  
Sunlight → Battery → Lamps  
System cost: \$USD 216,858

**438**  
tons of CO<sub>2</sub>e

