A Two-Stage Framework for Power System Resilience Assessment: Process Design and a Case Study in Kinmen

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Content Overview

01 Introduction

Motivation

- As the intermittent renewables penetration rate increases, the change in the power mix will **challenge the grid**.
- In addition, due to extreme weather phenomena, the public has been drawn to the **power system's long-ignored concept: resilience**.
- Since there is **no mature analysis framework and resilience metrics**, we
  - **propose** a two-stage analysis framework and generalized resilience metrics.
  - **apply** the framework and metrics to do a case study in the Kinmen power system.

Literature Review: Definition of Resilience

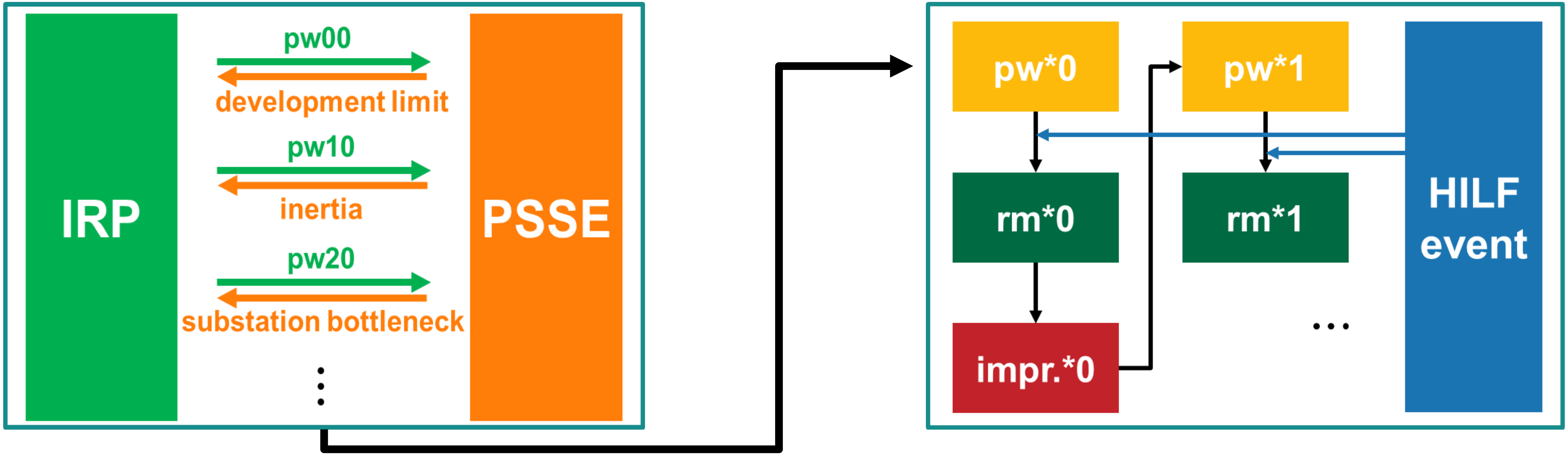
- **Reliability and resilience have been confusing in literature**.
- However, the majority views them as **different concepts** in recent study.
  - **Reliability**
    - It defines how a power system responds to low-impact high-frequency events (LIHF events).
    - The performance metrics include LOLE (Loss of Load Expectation), LOLP (Loss of Load Probability), EUE (Expected Unserved Load), and so on.
  - **Resilience**
    - It defines how a power system responds to **high-impact low-frequency events (HILF events)**.
    - The performance metrics **are still under discussion, and there is no universal standard.**
- In this study, we focus on resilience assessment.

Literature Review: Resilience Metrics

- Resilience Metrics (RMs) measure **how the power system performs when facing a HILF event in multiple aspects**.
  - How severe will the system be?
  - How fast will the system deteriorate/ recover?
  - Is the system relatively stable/ fluctuated during the event?
  - Is the system completely recovered?
- **The trajectories of loss of load and frequency** are most used as the system performance indicators.

Two-stage Resilience Assessment Framework

- We proposed a two-stage resilience assessment framework to plan a **resilient decarbonization pathway**.



Stage 1
Practical System Planning

Stage 2
Resilience Assessment

Case Study: Kinmen Region in 2030

- To elaborate on the analysis framework, we conduct a case study on the Kinmen Region (**small-scaled and isolated grid from Taiwan**).
- Assume that Kinmen Region aims to **reduce the carbon intensity to 0.4kg of CO_2e per kWh in 2030** (0.6kg as of 2022).
- The two-stage resilience assessment framework was applied.
  - Stage 1: IRP (integrated resources planning) and PSSE (power system simulator engineering) are used to design **a least-cost and practical feasible decarbonization pathway that meets the target.**
  - Stage 2: Based on the pathway designed in Stage 1, **RMs and improvement measures are iteratively calculated and considered.**

02 Practical System Planning

Least-cost & Feasible Decarbonization Pathway

- Given the 2030 carbon intensity target, we can obtain the least-cost energy portfolio by pure IRP model (pw00).
- We further **check the practical and development limitations** and **examine the grid stability with PSSE** to ensure the planning is reality-feasible iteratively.

Power System Configuration in Kinmen

Decarbonization Pathway	Heavy Oil	Diesel	Wind	Solar PV	Battery Storage	Load
	MW				MW/ MWh	GWh
As of 2023	87.6	26	4	21.4	9.8/ 60.8	317.9
pw00	87.6	26	24	365.0	49.9/ 196.4	400.52
pw10	87.6	27	5.8	153.7	53.5/ 210.4	
pw*0	**87.6**	**27**	**5.8**	**155.7**	**45.6/ 179.2**	

Limitations and Stability Checks

From pw00 to pw10

- The expansion of wind turbines is **against by the locals**, so the maximum potential is expected to be 5.8MW at most.
- Considering the **required system inertia**, two thermal units should always provide at least 4MW each.

From pw10 to pw*0

- The siting of newly added solar PV may cause bottleneck issues in some substations if allocated proportionally to current solar PV siting. We distribute solar PV using **the maximum capacity of solar PV connection.**
- We also examine **the solar PV geographic potentials** to see whether the connection way is feasible.

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03 Resilience Assessment

Resilience Assessment Framework

- Assessment Framework
  - **Determine the HILF event** and **characterize the direct impact.**
  - Based on the equipment's **fragility curve**, determine the probability of damage under the direct impact.
  - Traverse all equipment's status and **establish outcomes**.
  - Analyze the outcomes to determine the **impacts on the power system**.
  - **Calculate selected RMs**.
- Theoretically, this assessment framework **can be applied to any HILF events** if the required information is available.

Characteristics of Kinmen Region Power Grid

- Most of the transmission lines in Kinmen have been underground, making them less susceptible to external interference.
- Instead, **the damage to the switchyard and substation will cause a severe impact on the power grid.**

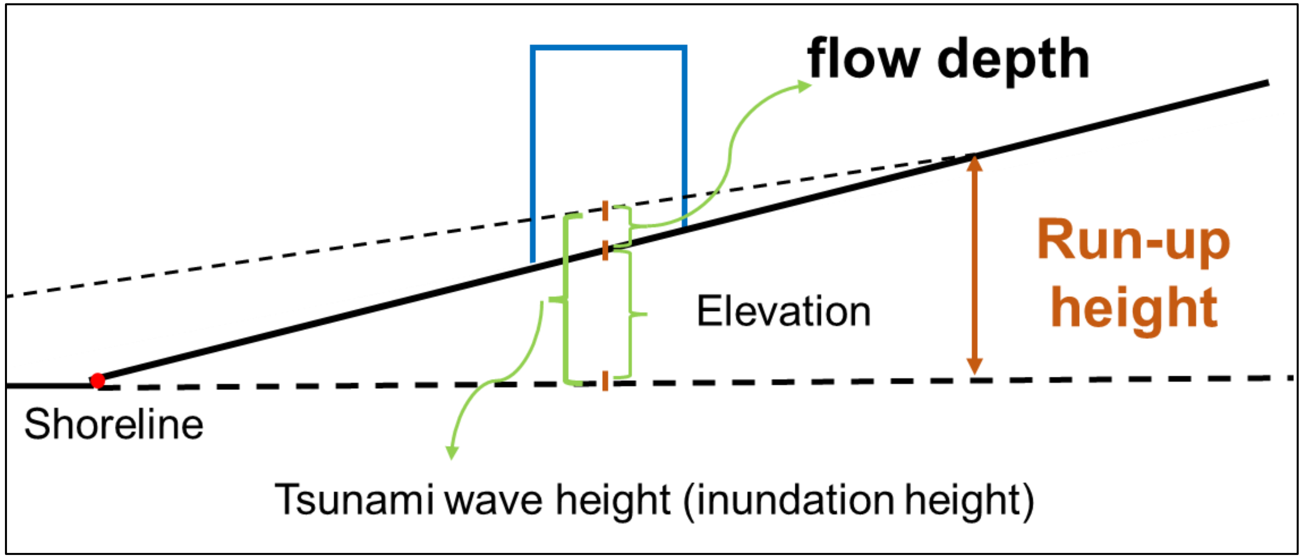
Switchyard and Substations in Kinmen

Determination of HILF Event

- **What kind of HILF event may cause damage to these facilities?**
  - Strong Wind: Limited damage.
  - Flood: Potential damage. Guning is **not** in the potential flood area.
  - Earthquakes: Potential damage. **No** fault zone under Kinmen.
  - High Ambient Temperature: Potential damage. **Limited** quantitative literature is available.
  - **Tsunami: Potential damage. Several facilities are located in the potential area where tsunami may strike.**
- **In this study, we analyze the resilience of the Kinmen power system when facing a 10m run-up height tsunami.**

Tsunami as the HILF Event

Tsunami Risk Map



Terminology of Tsunami

- Given a 10m run-up height tsunami, we can roughly estimate the flow depth that substations and switchyard may face.
- **Guning switchyard and Juguang substation** will **face a 4m and 1m flow depth tsunami strike** in this HILF event, respectively.

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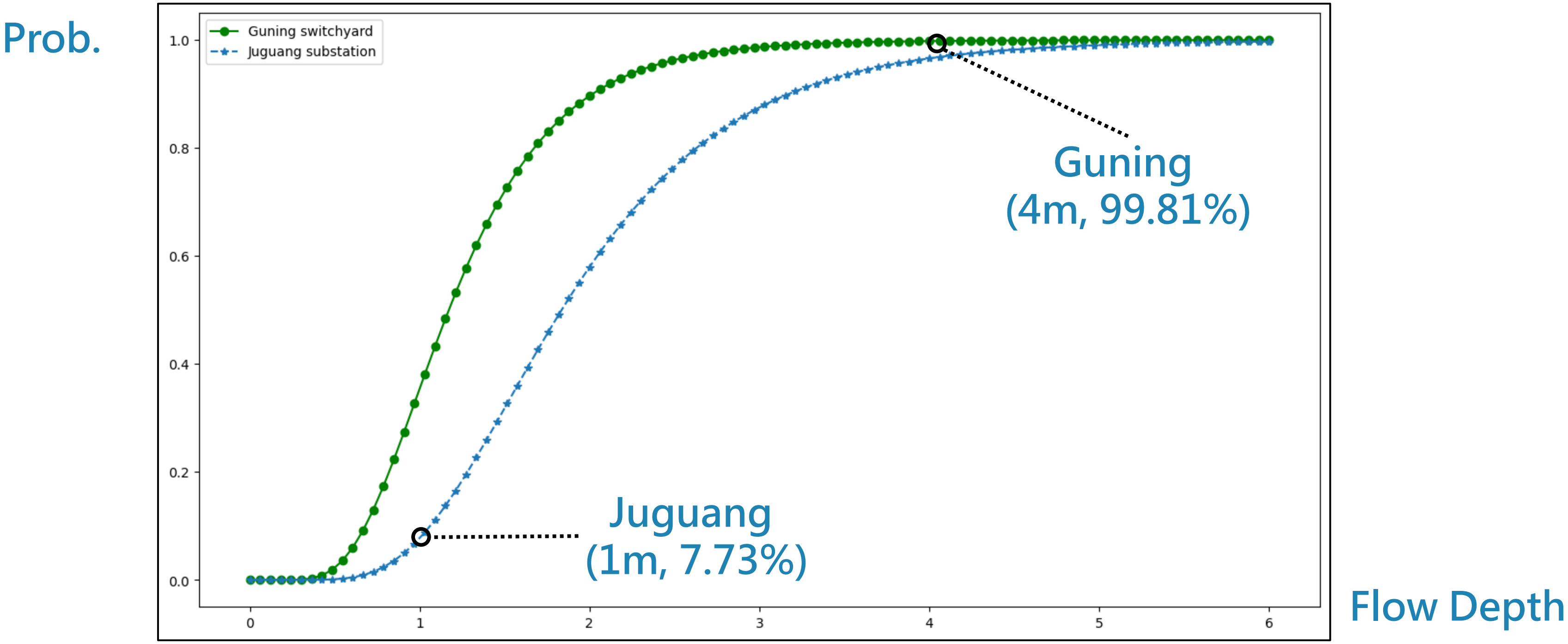
Fragility Curve



- Due to the limitation of fragility curve information, we ad hoc used the fragility curves that Federal Emergency Management Agency estimated.
- Two facilities are assigned different fragility curves, implying that the **Guning switchyard is more fragile** (temporary cement boundary walls).

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Outcomes

Outcomes	Guning	Juguang	Outcome Probability
oc1	X	V	92.09%
oc2	V	X	0.01%
oc3	X	X	7.72%
oc4	V	V	0.18%

- In our study, only two facilities are affected by the HILF event, so we can list all the possible outcomes and calculate the corresponding probability.
- We can further check the power system's response to different outcomes.

Scenarios to be analyzed

- In this study, we consider **different levels of storage centralization (cases)** and **different functions of storage (pathways)** to check whether the resilience performance can be improved.
  - Cases: Storage **distributed to 1 ~ 4 places**.
  - Pathways: w./ wo. **frequency response (fr)/ grid forming (gf)** functions.

Four Outcomes

oc1: GX/ JV
oc2: GV/ JX
oc3: GX/ JX
oc4: GV/ JV

Four Cases

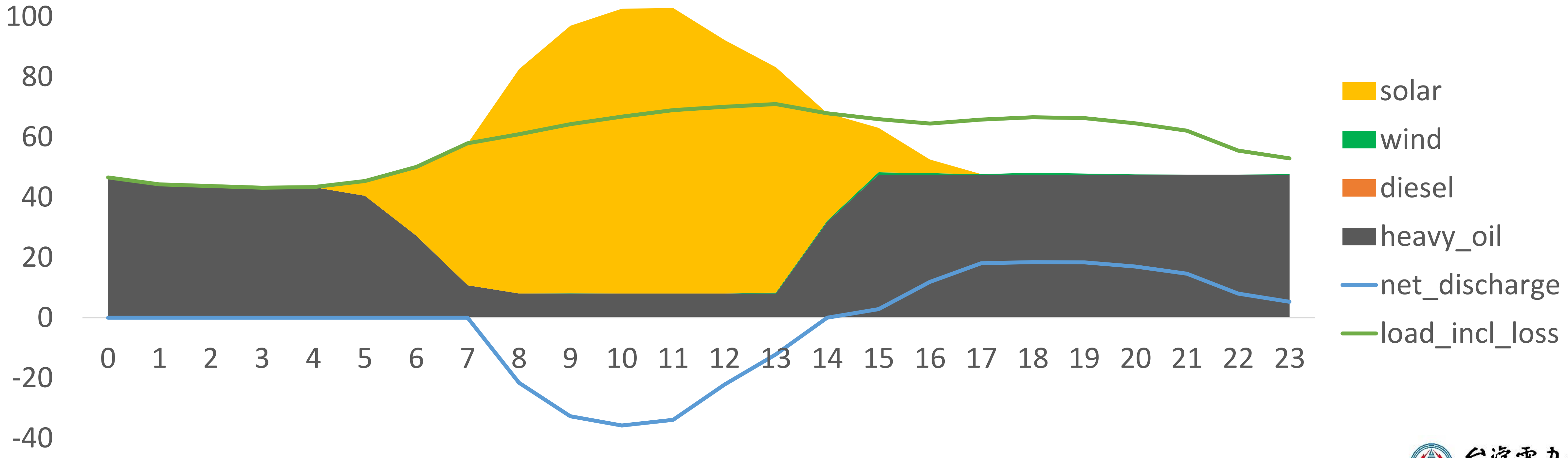
c1: 4 places
c2: 3 places
c3: 2 places
c4: 1 places

Three Pathways

pw*0: wo. fr, wo. gf
pw*1: w. fr, wo. gf
pw*2: w. fr, w. gf

Critical moment to be analyzed

- We conducted the resilience analysis at the time with the greatest projected solar PV output.
- At the moment, 90% of the **system load is served by solar PV**, and the **residual solar PV is charged by the battery storage**.



Power System Analysis (1/4)

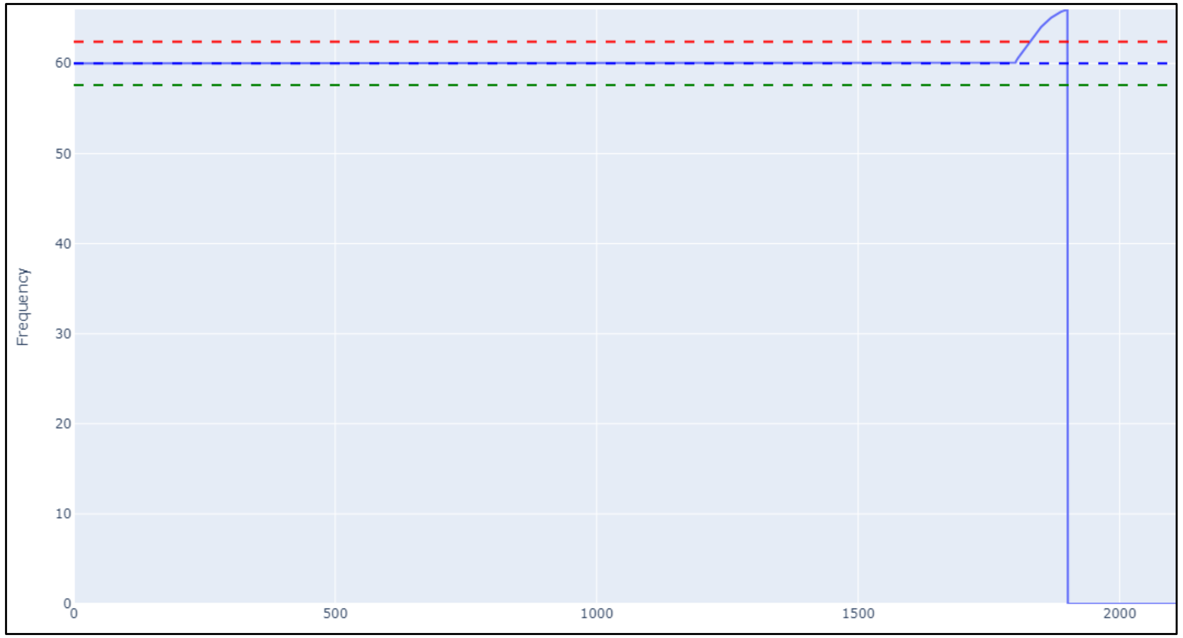
pw*0_oc1_c1

- No advanced storage system.

- Damaged Guning s.y.

- Decentralized storage (4 places)

- System frequency was pushed up for losing the storage at Guning (8.5MW).
- The frequency exceeds the diesel units' protection threshold (66Hz).
- The diesel units tripped, causing the system to lose the voltage source.
- The renewables tripped for no voltage source.
- **System failed.**



Resilience Curve (pw*0_oc1_c1)

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Power System Analysis (2/4)

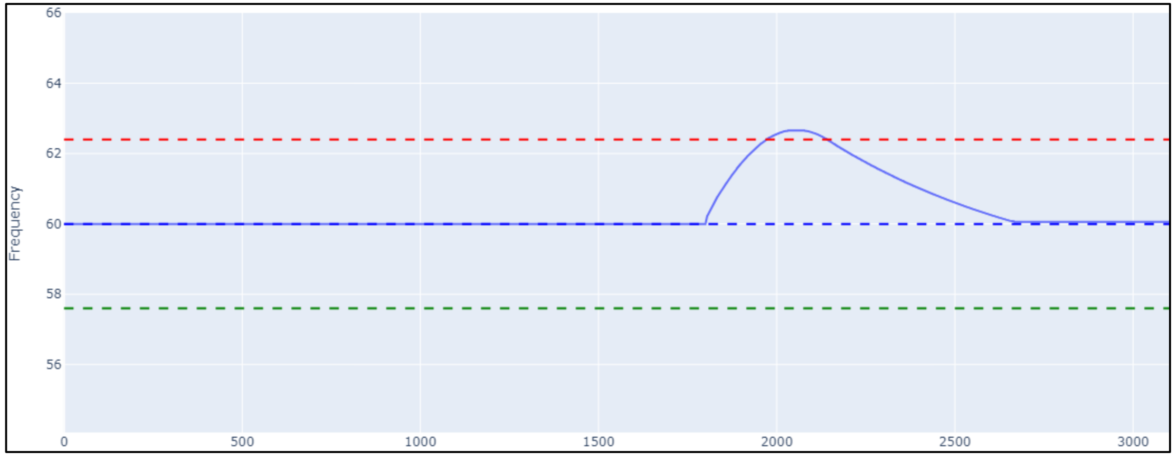
pw*2_oc1_c2

- Advanced storage system (grid-forming).

- Damaged Guning s.y.

- Decentralized storage (3 places)

- System frequency was pushed up for losing the storage at Guning (11.3MW).
- The frequency was pushed up without hitting the diesel units' protection threshold (66Hz) due to the advanced storage system.
- **System survived.**



Resilience Curve (pw*2_oc1_c2)

Power System Analysis (3/4)

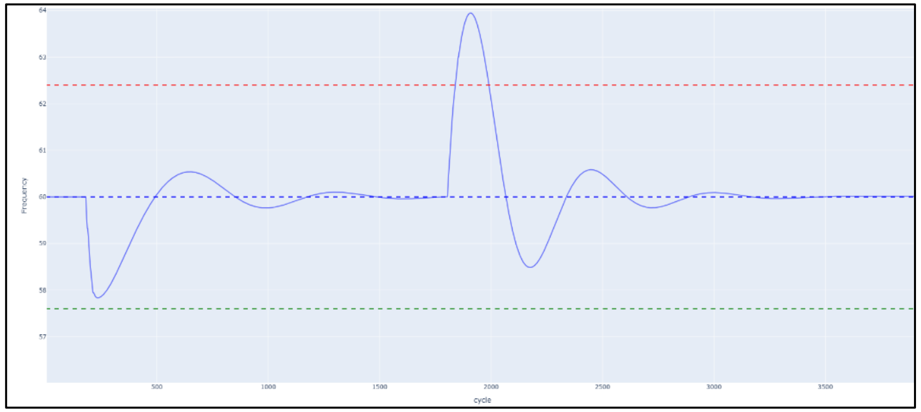
pw*1_oc3_c1

- Advanced storage system (frequency response).

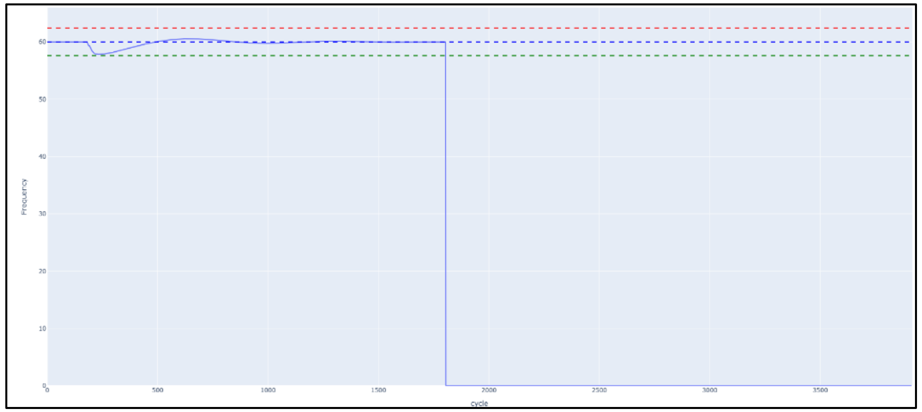
- Damaged Juguang s.s. & Guning s.y.

- Decentralized storage (4 places)

- System frequency dropped for losing the supply of solar PV from Juguang.
- The frequency was back to normal due to the advanced storage system.
- After 30s, Guning s.y. damaged.
- System split into TS & QS sub-systems.
  - TS was back to normal.
  - QS failed for losing the voltage sources (no generators or GFM in the subsystem).
- **System partially survived.**



Resilience Curve (pw*1_oc3_c1_TS)



Resilience Curve (pw*1_oc3_c1_QS)

Power System Analysis (4/4)

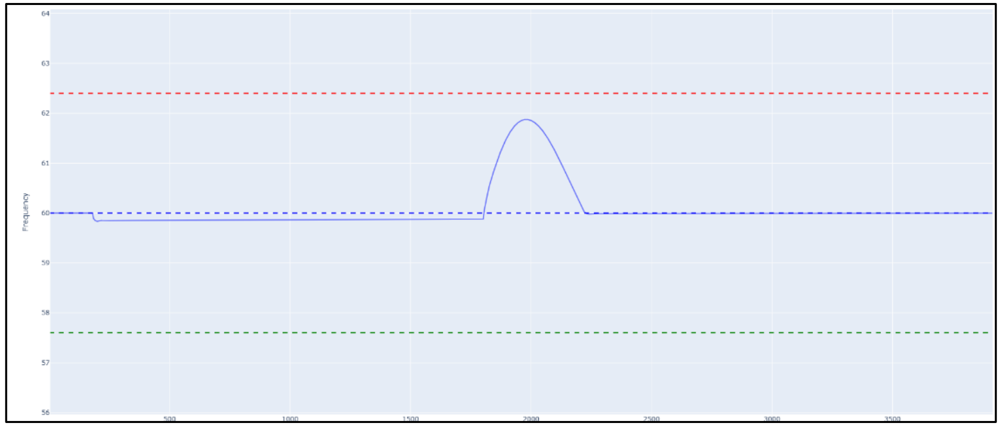
pw*2_oc3_c1

- Advanced storage system (grid-forming).

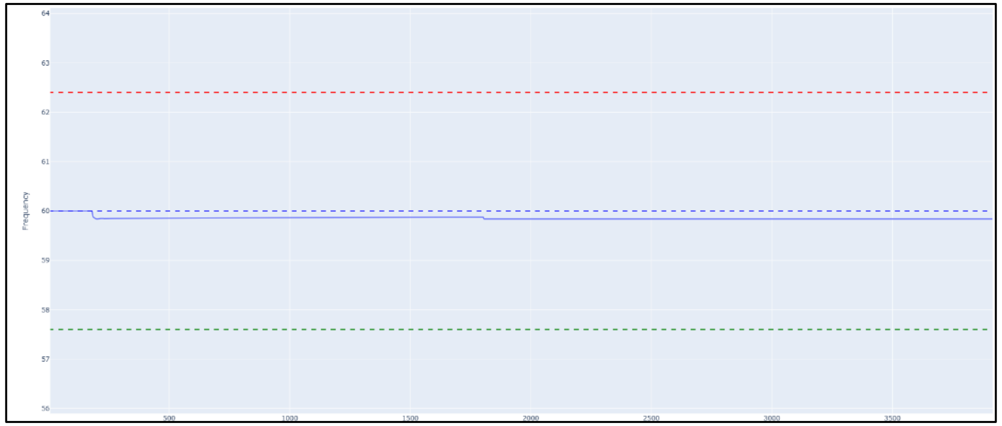
- Damaged Juguang s.s. & Guning s.y.

- Decentralized storage (4 places)

- System frequency dropped for losing the supply of solar PV from Juguang but recovered soon for the advanced storage.
- After 30s, Guning s.y. damaged.
- System split into TS & QS sub-systems.
  - TS was back to normal.
  - QS was back to normal for the support of grid-forming inverters.
- **System survived.**



Resilience Curve (pw*2_oc3_c1_TS)



Resilience Curve (pw*2_oc3_c1_QS)

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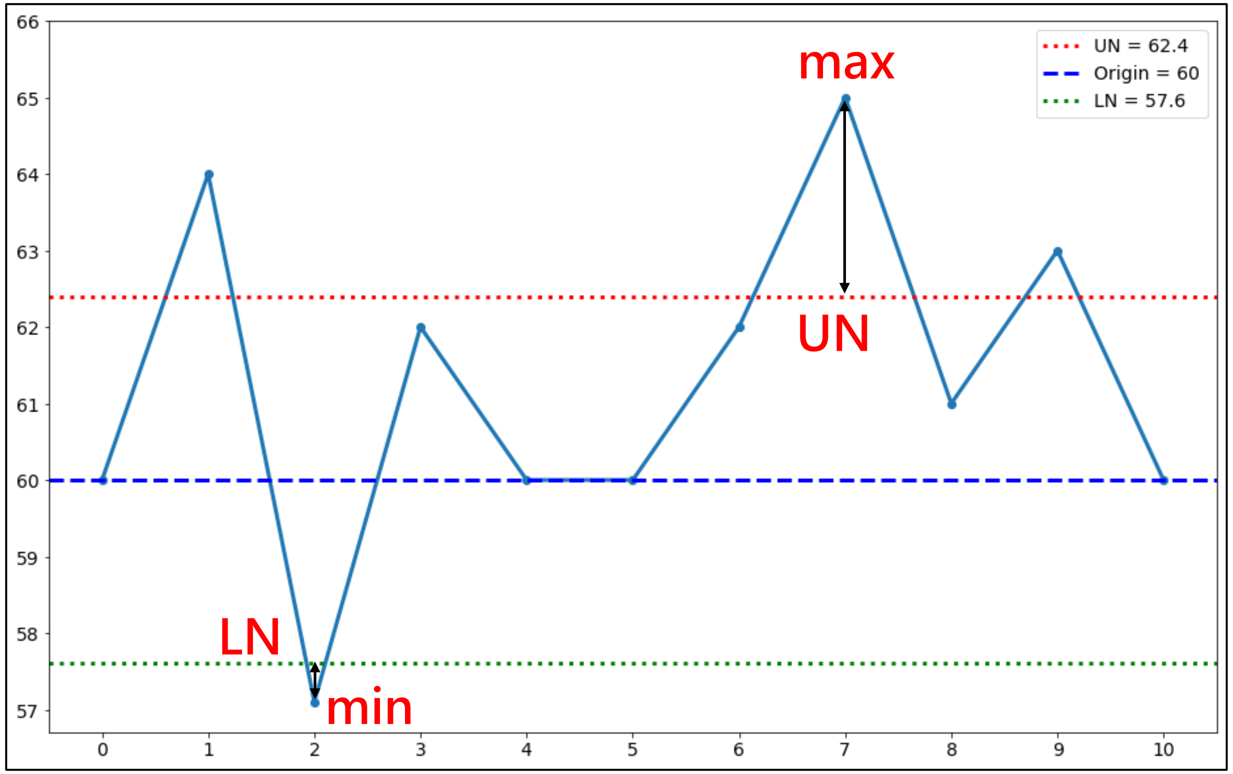
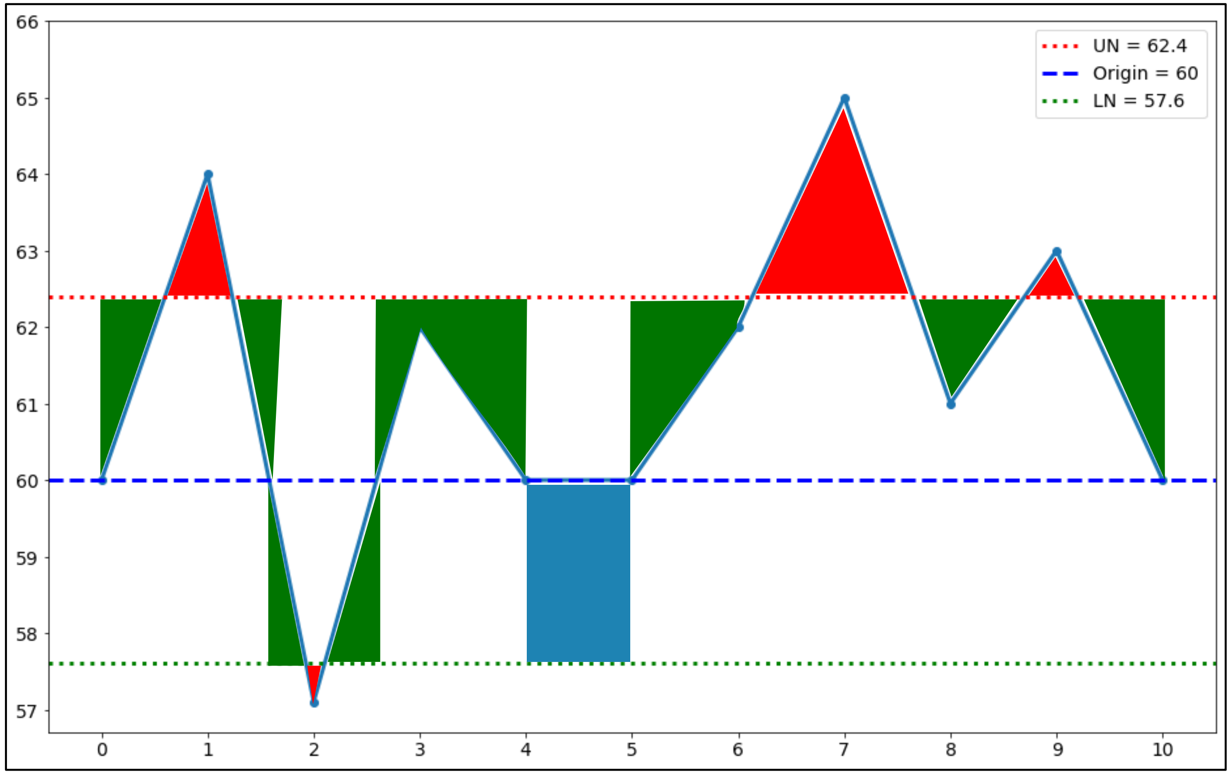
Generalized Resilience Metrics (1/3)



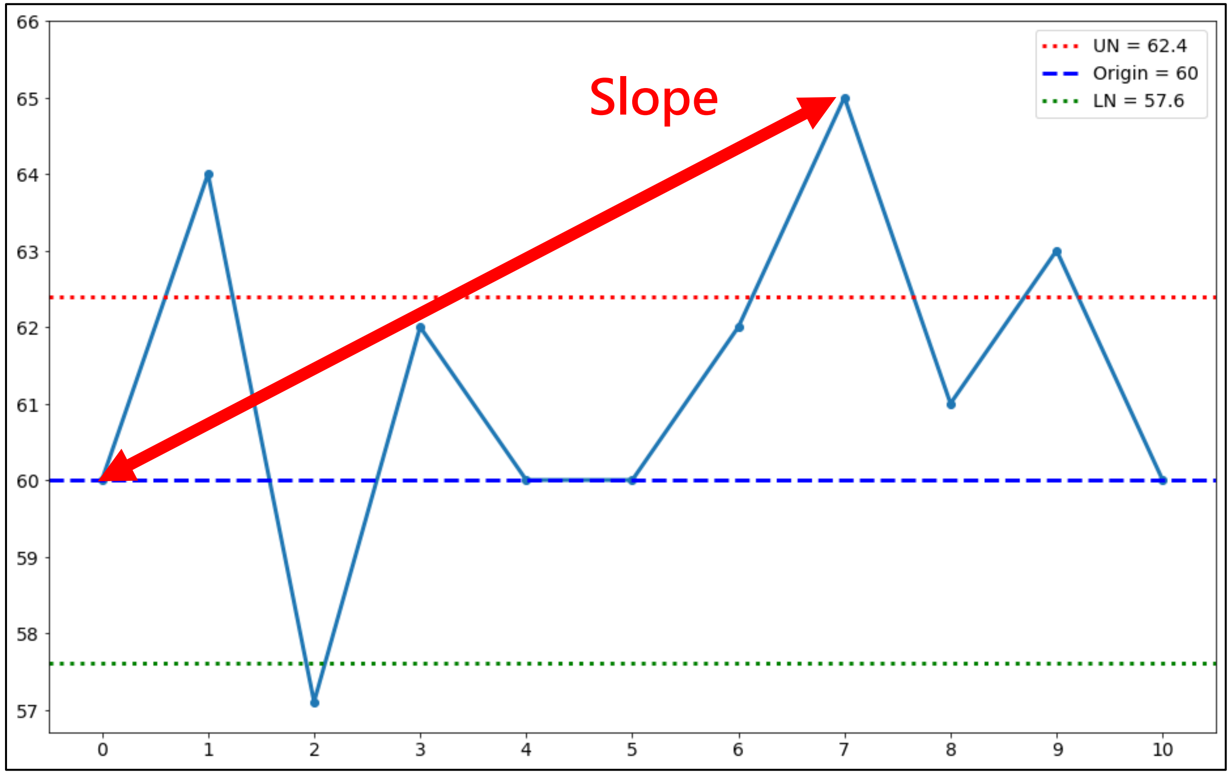
Adaptation

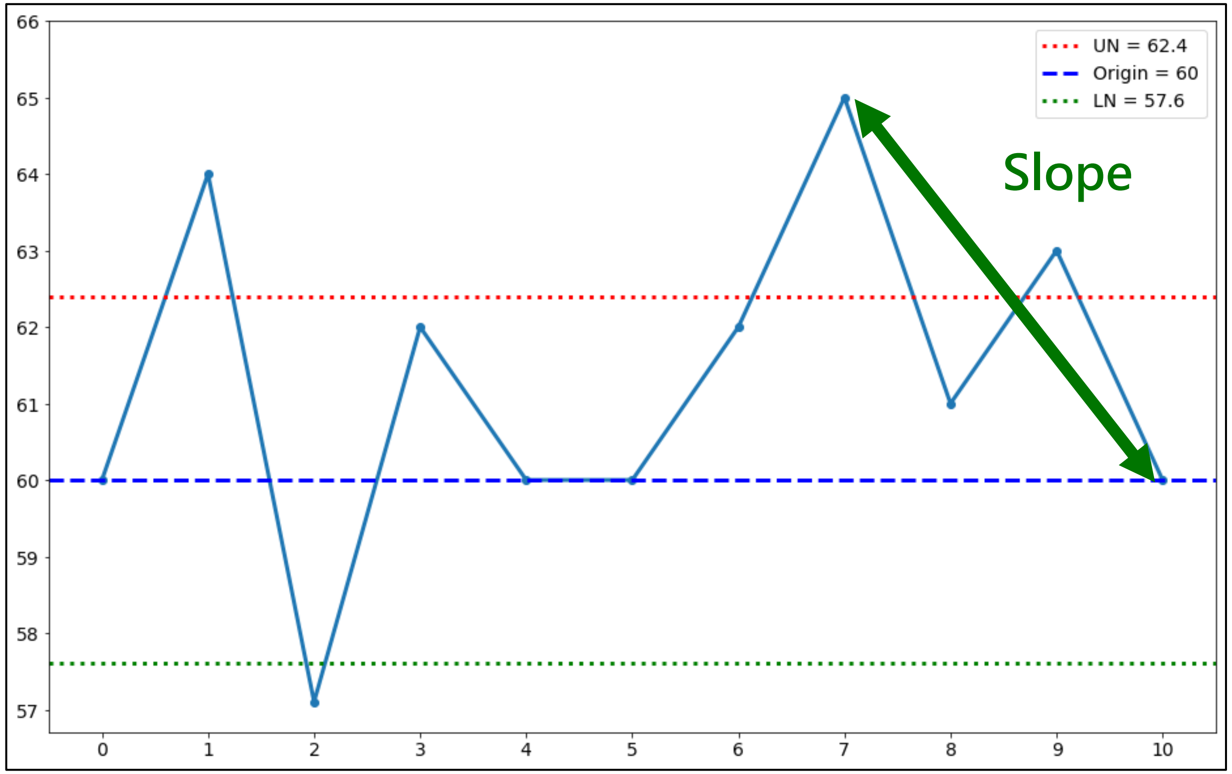


Robustness

Brittleness

Generalized Resilience Metrics (2/3)

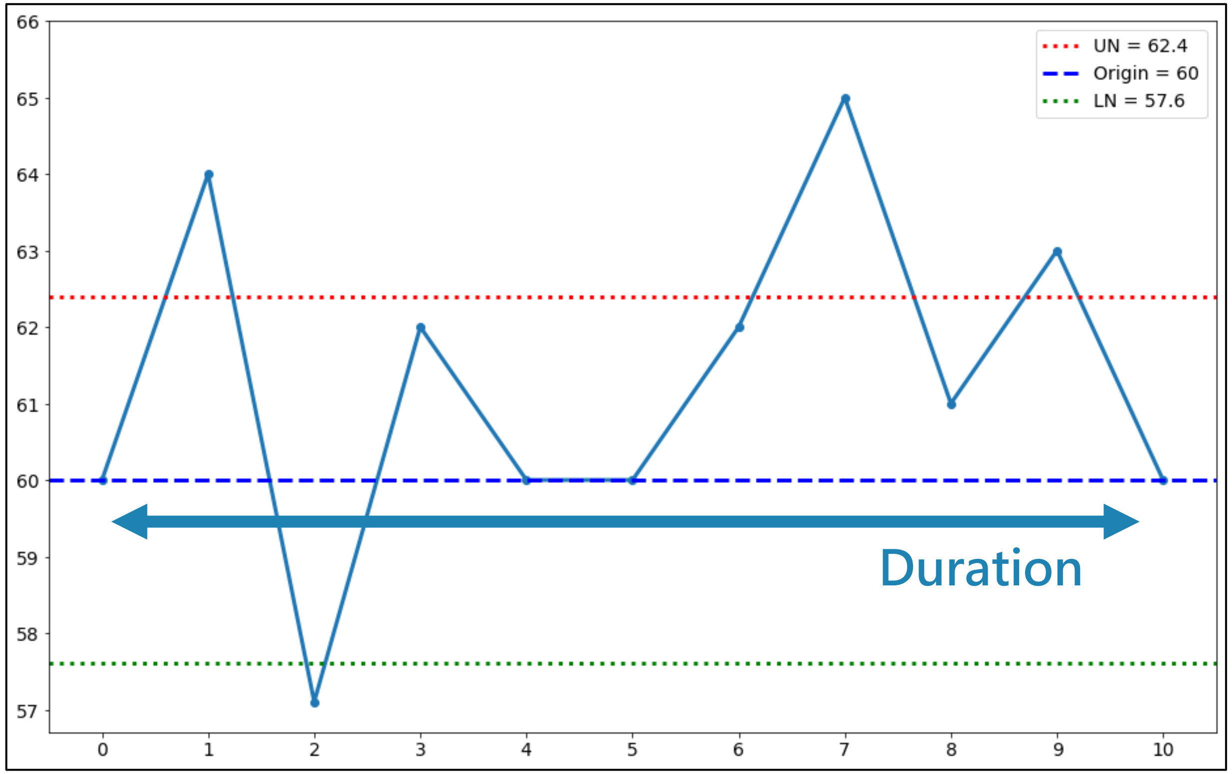




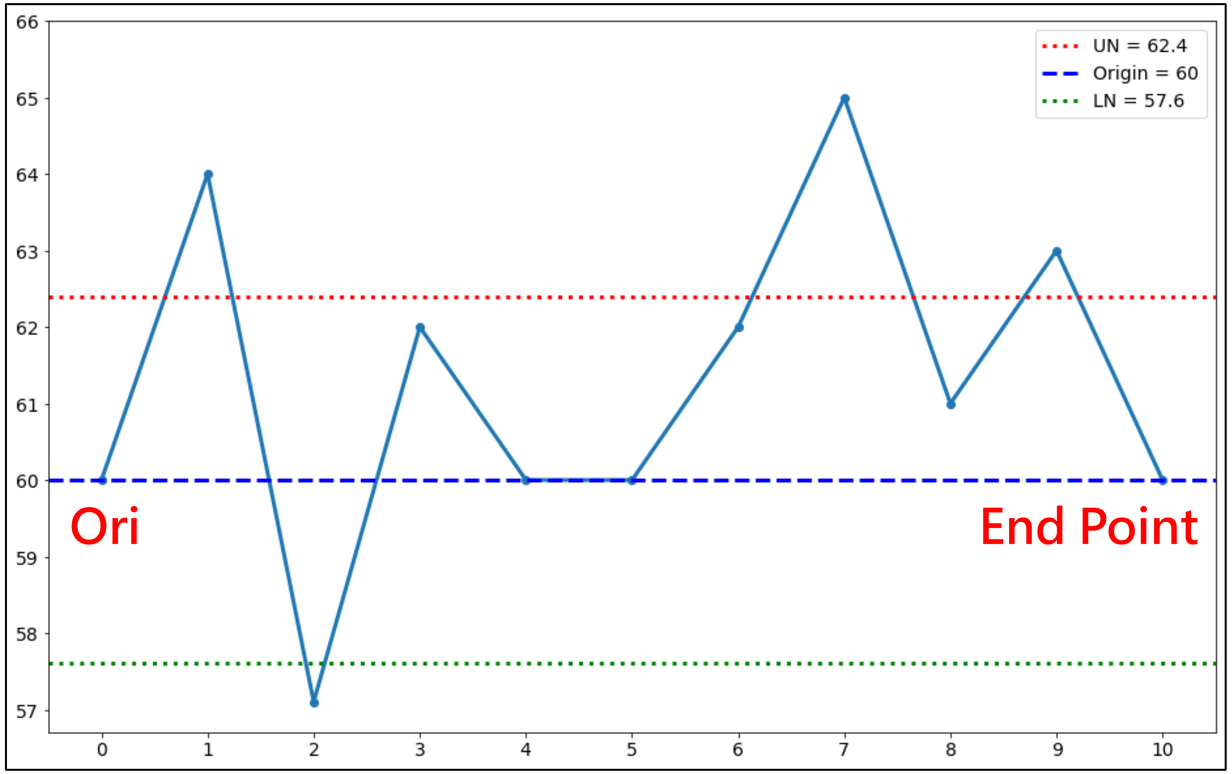
Agility (deterioration resistance)

Agility (reverse restoration)

Generalized Resilience Metrics (3/3)



Duration



Recovery Rate

Expectation Value of Resilience Metrics

- Expectation values of RMs can be calculated with the outcome probability.
- The RM values have been processed to be more straightforward.
  - **Standardized to [0, 1].**
  - **The larger, the better.**

Storage system Functions	Scenarios	Expectation Value of Resilience Metrics							
		Load Lost (MW)	Adapt.	Robust.	Brittle.	Agility (deterioration)	Agility (restoration)	Duration	Recovery Rate
wo. fr/ wo. gf.	pw*0_c1	68.8359	0.0090	0.4172	0.4178	0.8922	0.0018	0.0018	0.0018
	pw*0_c2	68.8359	0.0091	0.4074	0.4077	0.8915	0.0018	0.0018	0.0018
	pw*0_c3	68.8359	0.0097	0.4022	0.4023	0.8910	0.0018	0.0018	0.0018
	pw*0_c4	68.8359	0.0112	0.3982	0.3982	0.8907	0.0018	0.0018	0.0018
w. fr/ wo. gf.	**pw*1_c1**	**4.5432**	**0.8957**	**0.9782**	**0.9818**	**0.9970**	**0.5613**	**0.0561**	**0.9688**
	pw*1_c2	**4.5432**	**0.8875**	**0.9778**	**0.9816**	**0.9949**	**0.6241**	**0.0552**	**0.9687**
	pw*1_c3	68.0485	0.0491	0.4628	0.4631	0.9657	0.0102	0.0039	0.0479
	pw*1_c4	68.8321	0.0069	0.4315	0.4317	0.9653	0.0018	0.0018	0.0019
w. fr/ w. gf.	**pw*2_c1**	**2.3917**	**0.9837**	**0.9977**	**1**	**0.9994**	**0.2431**	**0.1194**	**0.9992**
	pw*2_c2	**2.3917**	**0.9623**	**0.9944**	**0.9999**	**0.9985**	**0.8134**	**0.2509**	**0.9990**
	pw*2_c3	68.0485	0.0506	0.5095	0.5115	0.9704	0.0018	0.0112	0.0479
	pw*2_c4	68.8321	0.0071	0.4316	0.4316	0.9653	0.0018	0.0018	0.0019

04 Final Remarks

Observations (1/3)

- A power system with an **advanced storage system** can significantly **improve system resilience performance**.
  - If the energy storage system does not have frequency response or grid-forming capabilities, the power system will **hardly survive** in our assumed HILF event.
  - This observation aligns with our expectations, especially in power systems with a higher proportion of renewable energy sources, where the role of energy storage will be more critical.
  - More specifically, energy storage not only **balances supply and demand differences** but also allows for greater integration of renewable energy **without assistance from traditional thermal power units**.

Observations (2/3)

- **Decentralized storage allocation** design generally **improves the system resilience performance**.
    - For those examples where **energy storage devices are concentrated in one or two locations (c3 & c4)**, the power system appears **unable to survive** the HILF event.
    - This observation seems to demonstrate the **importance of risk diversification.**

Observations (3/3)

- **The resilience metrics we proposed** in this study can **reflect the status of the power system in multiple aspects**.
  - Comparing the convergent and outage scenarios, it can be found that the former has a larger value while the latter has a smaller value of RMs.
  - The observation above implies that the RMs proposed in this study can **faithfully reflect the power system's response to HILF events.**
  - Based on the simulation results in this case study, when a scenario performs well in specific resilience metrics, it usually performs well in other ones.

Contributions

- In this study, we proposed a **two-stage resilience assessment framework** to **plan a least-cost, practical-feasible, resilient decarbonization pathway**.
- We also proposed **a set of generalized resilience metrics** to measure the **system resilience performance** under the HILF event.
- We **conducted a case study on the Kinmen Region** to elaborate on the feasibility of the **assessment framework and generalized resilience metrics** we proposed.