Exploring Symbiotic Synergies in Hybrid Wind-Wave Energy Systems for Enhanced Efficiency and Cost Reduction

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Hybrid wind-wave energy systems

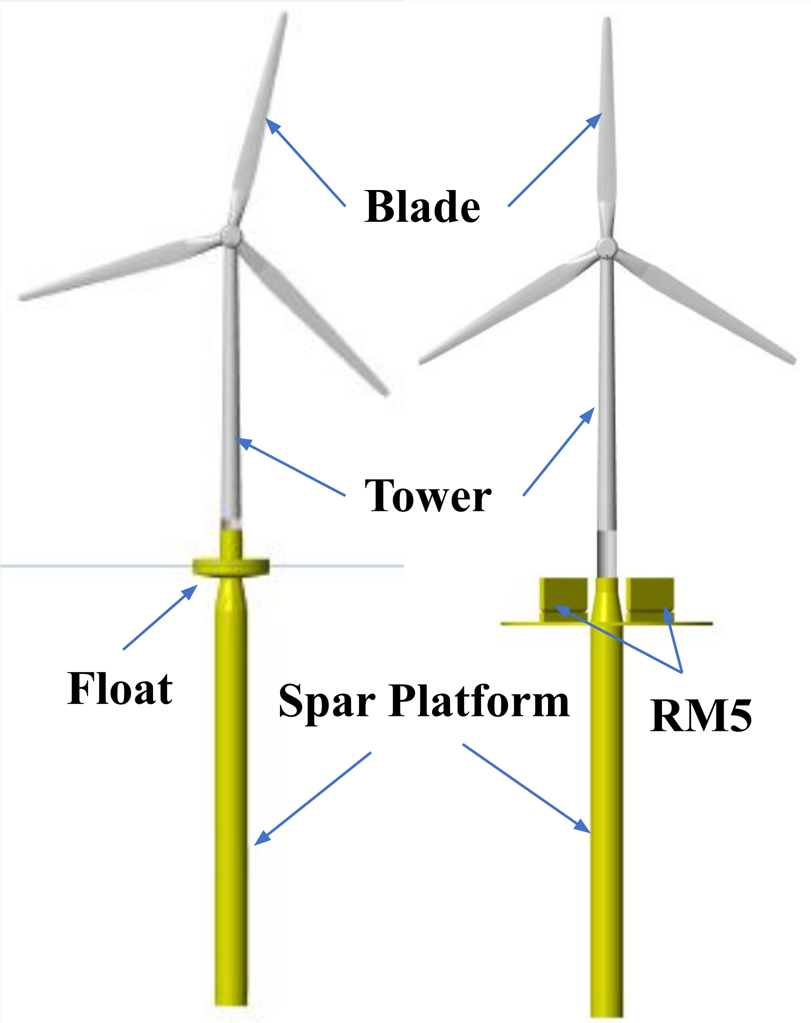
- Renewable energy demand is rising globally.
- Wind and wave energy are abundant offshore resources.

Economic Benefits:

- 43% lower LCOE for wave converters[1]
- Lower operational costs[1,2]
- Improved competitiveness in the energy market[1,2]

Goal of this work:

- assess economic viability (**LCOE, synergy, and power variation**) using a novel coupled simulation framework.

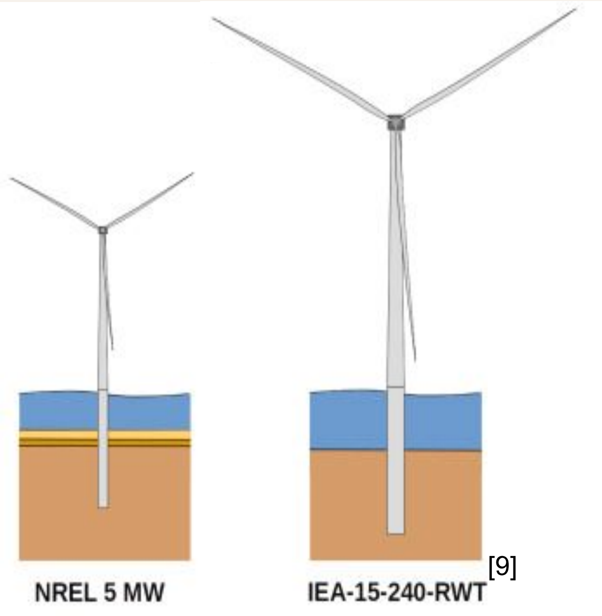


[1] Kluger, Haji, & Slocum. (2023) *Applied Energy.* 331, 120389.
[2] Feng et al. (2023) *Ocean Eng.* 285, 115401.

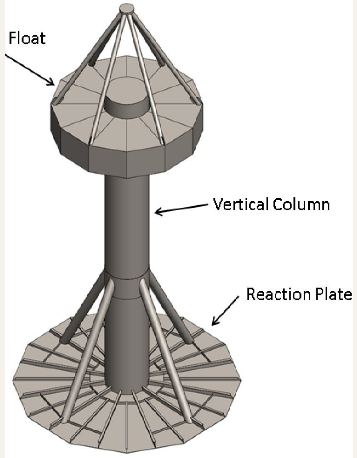
Case studies

Investigate the combination of wind turbines with different WECs and compare it to standalone system

- Two WTs: **5MW**[3] and **15MW**[4] RWTs
- Two WECs: **RM3**[5] (PA) and **RM5** [6] (OSWEC)
- Two mooring foundations: **OC3**[7] and **OC4**[8] (spar and semi-submersible)
- One location: **Eureka, CA**

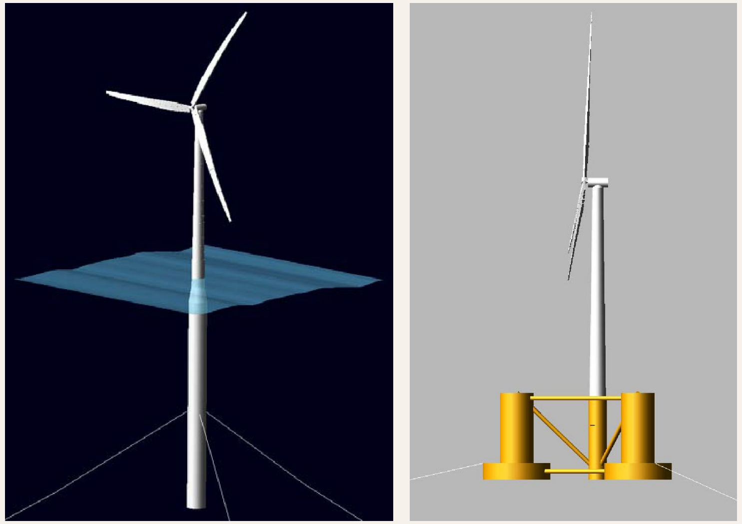


[9]



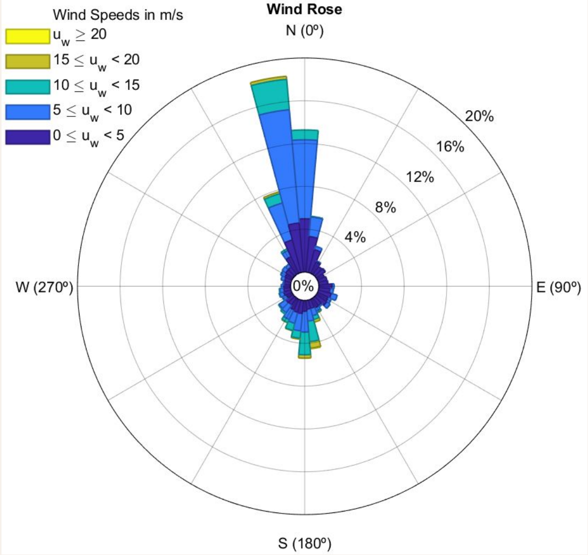
RM3 [5]

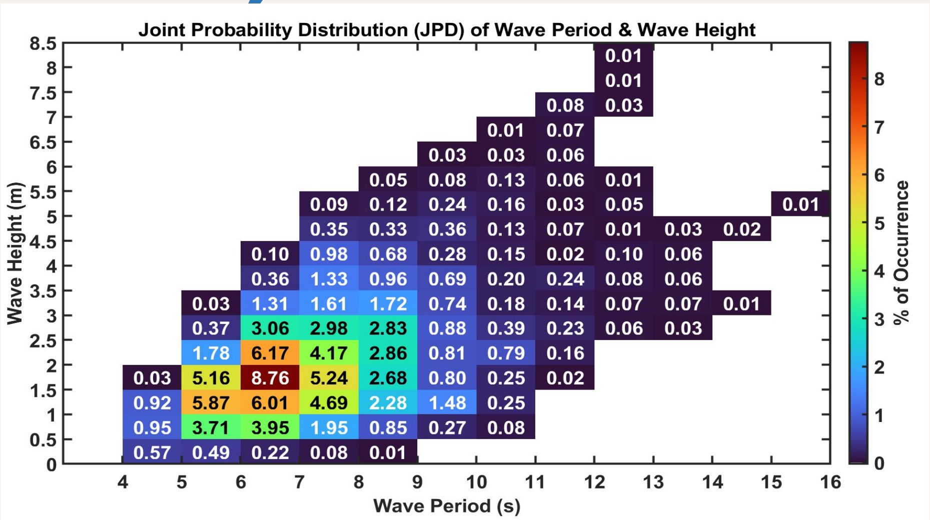

RM5 [6]

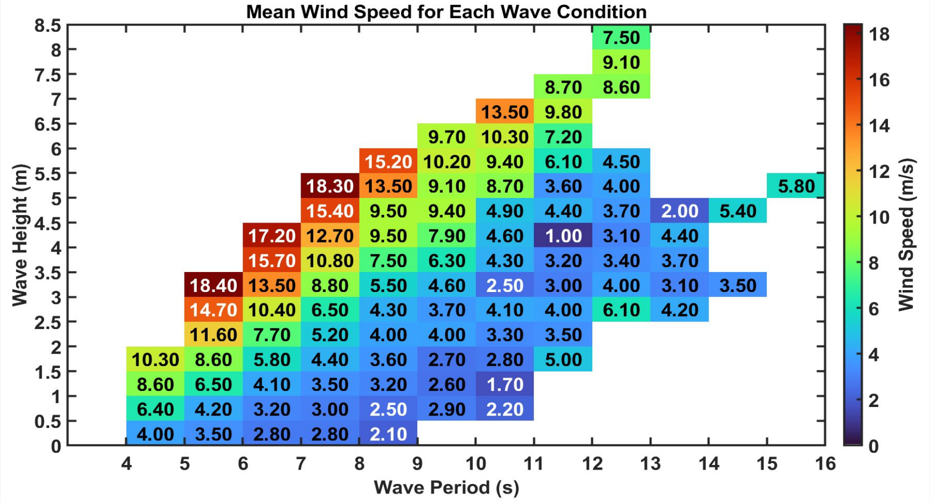

OC3 and OC4 [7, 8]

[3] https://www.nrel.gov/docs/fy09osti/38060.pdf
[4] https://www.nrel.gov/docs/fy20osti/75698.pdf
[5] https://energy.sandia.gov/wp-content/gallery/uploads/SAND2014-9040-RMP-REPORT.pdf
[6] https://www.nrel.gov/docs/fy15osti/62861.pdf
[7] https://doi.org/10.2172/979456
[8] https://doi.org/10.2172/1155123
[9] https://doi.org/10.1016/j.oceaneng.2022.111653

Wind and wave resources: Eureka, CA







- The annual energy production (**AEP**) of the hybrid system depends heavily on the site resources, particularly **wind speed**, dominant **wave period**, and significant **wave height**.

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Numerical modeling – Coupled framework

Software/Tools:

- Rhino CADs and Mesh
- NEMOH Mesher Refining the mesh
- NEMOH Hydrodynamics in frequency domain
- WEC-Sim Hydrodynamics in time domain
- TurbSim Wind
- MOST Aerodynamics and Controller
- MoorDyn Mooring loads
- WEC-Sim+MOST+MoorDyn Hybrid wind-wave system

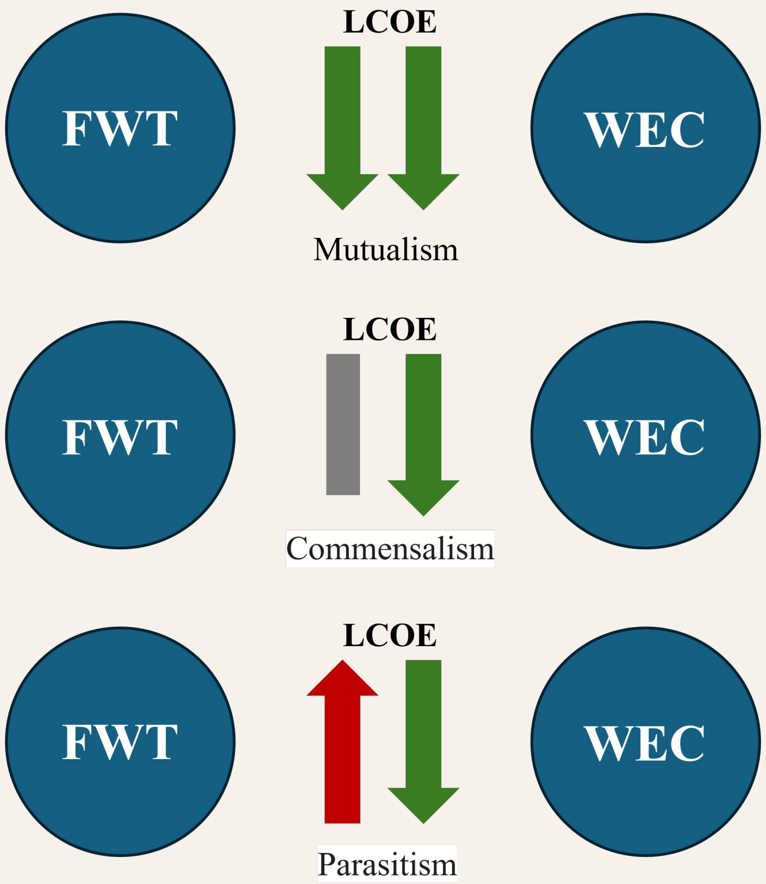
Synergy and symbiosis

Types of Symbiosis[9]:

- **Mutualism**: Both FWT and WEC benefit from integration
- **Commensalism**: WEC benefits; FWT is unaffected
- **Parasitism**: WEC benefits; FWT is negatively impacted

Use **LCOE** to assess integration effectiveness.

- **Mutualism**: LCOE **decreases** for **both** devices
- **Commensalism**: LCOE **decreases** for **one**, unchanged for the other
- **Parasitism**: **LCOE decreases** for **one**, **increases** for the other



[9] Garcia-Sanz M. (2024) *Advanced Control for Applications: Engineering and Industrial Systems.*

Hybrid System – PA (Float)

6 Configurations

WT	WEC	Platform Type
5MW	RM3	Spar
		Spar with reaction plate
		Semi-submersible
15MW	RM3	Spar
		Spar with reaction plate
		Semi-submersible

LCOE for Eureka, all configurations

- A **100-unit** array of each configuration is considered and evaluated.

	5MW					15MW				
	Spar	Spar+Float	Spar+Float +Plate	Semi	Semi +Float	Spar	Spar+Float	Spar+Float +Plate	Semi	Semi +Float
AEP (GWh)	8.42	9.08	9.53	8.28	9.06	27.80	28.20	28.59	28.37	29.19
CAPEX ($ 2025)	2.29E+09	2.43E+09	2.65E+09	2.78E+09	2.92E+09	6.51E+09	6.82E+09	7.17E+09	7.54E+09	7.85E+09
OPEX ($ 2025)	9.15E+07	9.15E+07	9.15E+07	9.15E+07	9.15E+07	2.75E+08	2.75E+08	2.75E+08	2.75E+08	2.75E+08
LCOE ($/MWh)	407.90	395.39	401.67	479.84	455.73	356.44	363.34	371.68	389.18	389.79

- **LCOE** is **lower** for hybrid system with the **5 MW WT, higher** with the **15 MW WT** on a **spar** and about the **same** on a **semi-submersible** platform.
- Adding the **cost** of the **reaction plate** is **compensated** for the **5 MW WT** but **not** the **15 MW WT**.

Synergy for Eureka, all configurations

	Standalone WEC	Standalone 5 MW WT		Standalone 15 MW WT	
	Spar platform	Spar platform	Semi-submersible platform	Spar platform	Semi-submersible platform
LCOE ($/MWh)	1373	407.9	479.84	356.44	389.18

	Hybrid 5 MW WT						Hybrid 15 MW WT					
	Spar platform		Spar platform with plate		Semi-submersible platform		Spar platform		Spar platform with plate		Semi-submersible platform	
	WEC	WT	WEC	WT	WEC	WT	WEC	WT	WEC	WT	WEC	WT
LCOE ($/MWh)	235.79	407.9	598.48	387.04	219.87	475.73	599.36	358.55	1162.4	354.19	423.23	388.85

- LCOE of **WEC** is **reduced** for **all** configurations.
- LCOE of **5 MW WT** is reduced in most configurations except with the spar remained unchanged - **all** cases have **mutualism; one** case has **commensalism**.
- LCOE of **15 MW WT** is reduced in most configurations except with the spar increased - **all** cases have **mutualism; one** case has **parasitism**.

Power coefficient of variation for Eureka, all configurations

- **Power generation** is directly **impacted** by the **availability** of wind and waves.
- Variability in wind and wave resources is reflected on power generation.

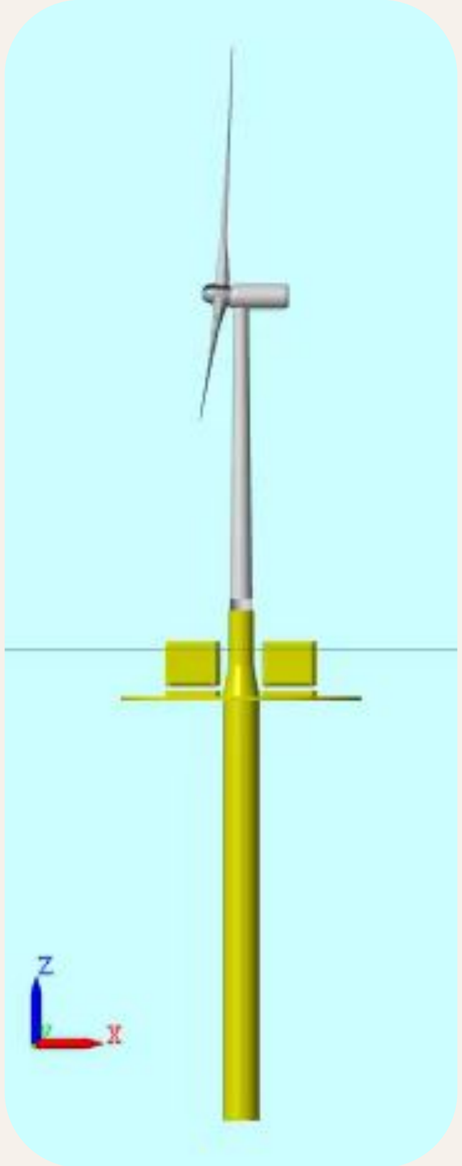
	Standalone WEC	Standalone 5 MW WT		Standalone 15 MW WT	
	Spar platform	Spar platform	Semi-submersible platform	Spar platform	Semi-submersible platform
CV	0.76	1.16	1.18	1.11	1.1

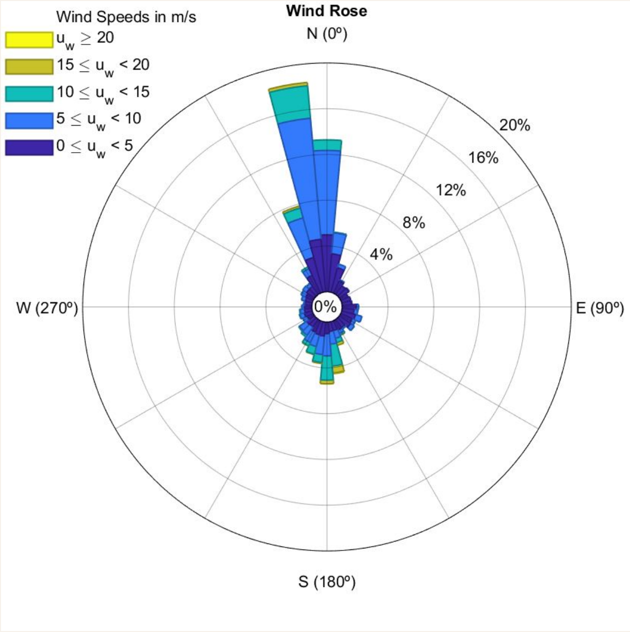
	Hybrid 5 MW WT			Hybrid 15 MW WT		
	Spar platform	Spar platform with plate	Semi-submersible platform	Spar platform	Spar platform with plate	Semi-submersible platform
CV	0.68	0.67	0.65	0.7	0.68	0.6

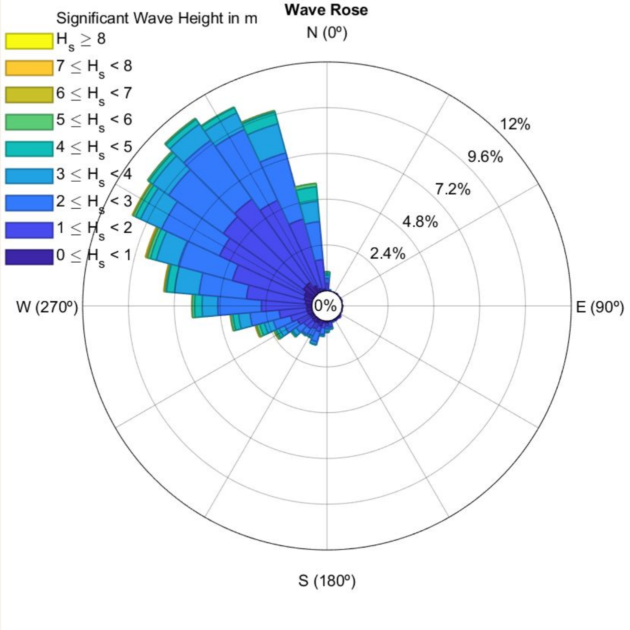
- **Hybrid systems** have more **stable power supply**, resulting in a **lower need** for **energy storage**.

Hybrid system – OSWEC

- **WECs** are rotated **45 deg** to face the waves.
- **Challenges** to stabilize the system:
  - Dynamic interaction between **pitching** motion of the WECs and the motion of the **spar.**
  - **Mooring** system: currently a **catenary** system, potentially **taut** system.







Conclusions

- **Site selection** for hybrid systems is **critical** to improve **performance** and **reduce LCOE**
- **WT** power is **not impacted** by hybridization; **WEC** power is **higher** in hybrid systems
- **LCOE** is **lower** for hybrid systems with **5 MW** WT
- **LCOE** is **unchanged** or slightly higher for hybrid system with **15 MW** WT
- **WEC benefits** from hybridization in **all configurations**
- **WT benefits** from hybridization in **all** configuration **except** with **spar platform**
- **All configurations** show **mutualism** except with spar platform:
  - **commensalism** with 5 MW WT
  - **parasitism** with 15 MW WT
- **Hybrid** systems have **lower power coefficient of variation,** leading to **more stable power supply** and **lower** need for **energy storage.**

Thank you!

Questions?

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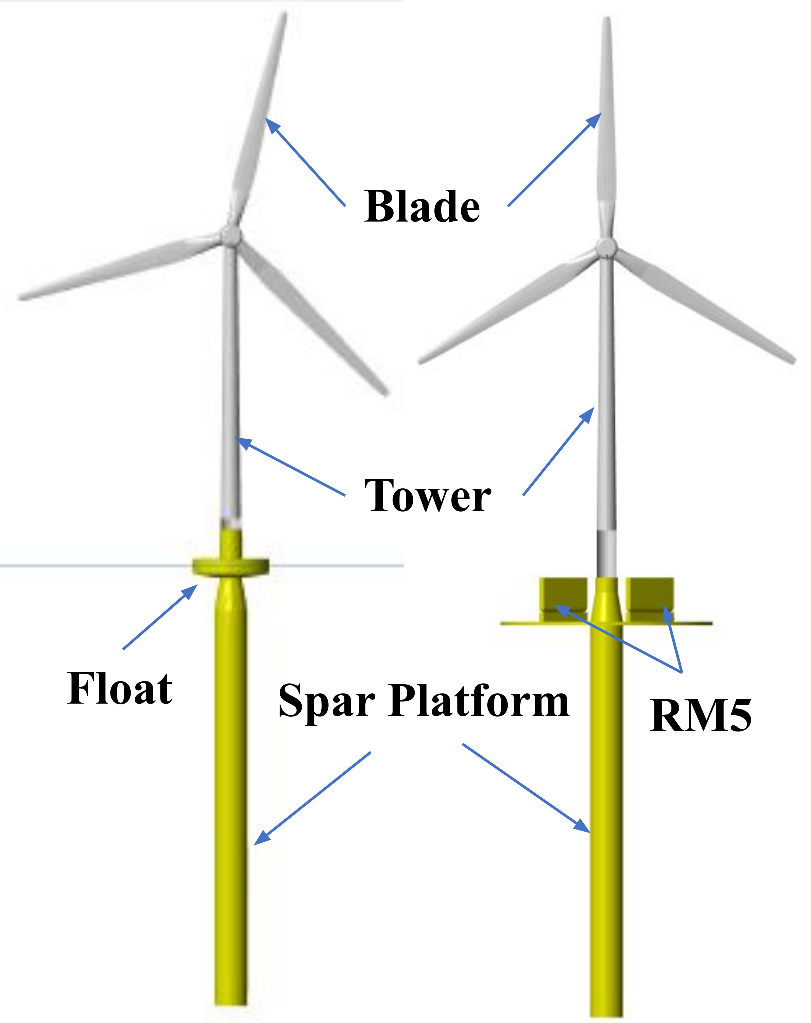
Hybrid wind-wave energy systems

- Renewable energy demand is rising globally.
- Wind and wave energy are abundant offshore resources.
- Annual energy potential:
  - Wave: 2,640 TWh, about 63% of the total U.S. need.[1]
  - Wind: 43,000 TWh in continental US[2] (greatly exceeds 2022 U.S. electricity use of 4,000 TWh[3]).

- **Goal of this work:** to assess economic viability (**LCOE, synergy, and power variation**) using a novel coupled simulation framework.



[1] US Energy Information Administration
[2] NREL https://www.nrel.gov/docs/fy17osti/65323.pdf
[3] U.S. EIA (2024) Total Electricity Net Consumption.

Benefits of hybrid wind-wave systems

Energy and Efficiency

- 15% smoother power output[4]
- 6% lower energy curtailment[4]
- 2% higher power efficiency[4]
- 20–35% reduction in storage needs[5]

Economic

- 43% lower LCOE for wave converters[4]
- Lower operational costs[4,6]
- Improved competitiveness in the energy market[4,6]

Goal of this work: to assess economic viability (LCOE, synergy, and power variation) using a novel coupled simulation framework.

[4] Kluger, Haji, & Slocum. (2023) *Applied Energy.* 331, 120389.
[5] Gao et al. (2024) *Renew. Sust. Energy Revs.* 192, 114263.
[6] Feng et al. (2023) *Ocean Eng.* 285, 115401.

Floats for hybrid system case studies

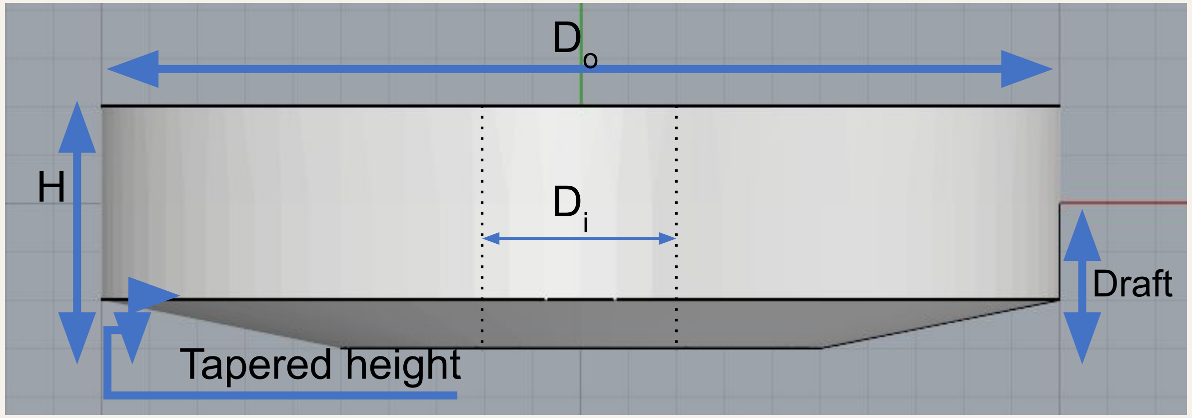
- Total no. of cases: 6 cases
- Total no. of floats to be optimized: 2 floats
- Trial and error optimization using Rhino, NEMOH, and WEC-Sim.
- In the future, use semi-analytical model (MEEM)[14].

WT	Case	Float Dimensions					
		Di (m)	Do (m)	H (m)	Draft (m) (%)	Tn (s)	Scale (RM3)
5MW	Spar	6.5	22	5	3 (60)	6.23	1.2
	Spar with reaction plate						
	Semi-submersible						
15MW	Spar	10	30	8	5 (63)	6.12	3.5
	Spar with reaction plate						
	Semi-submersible						

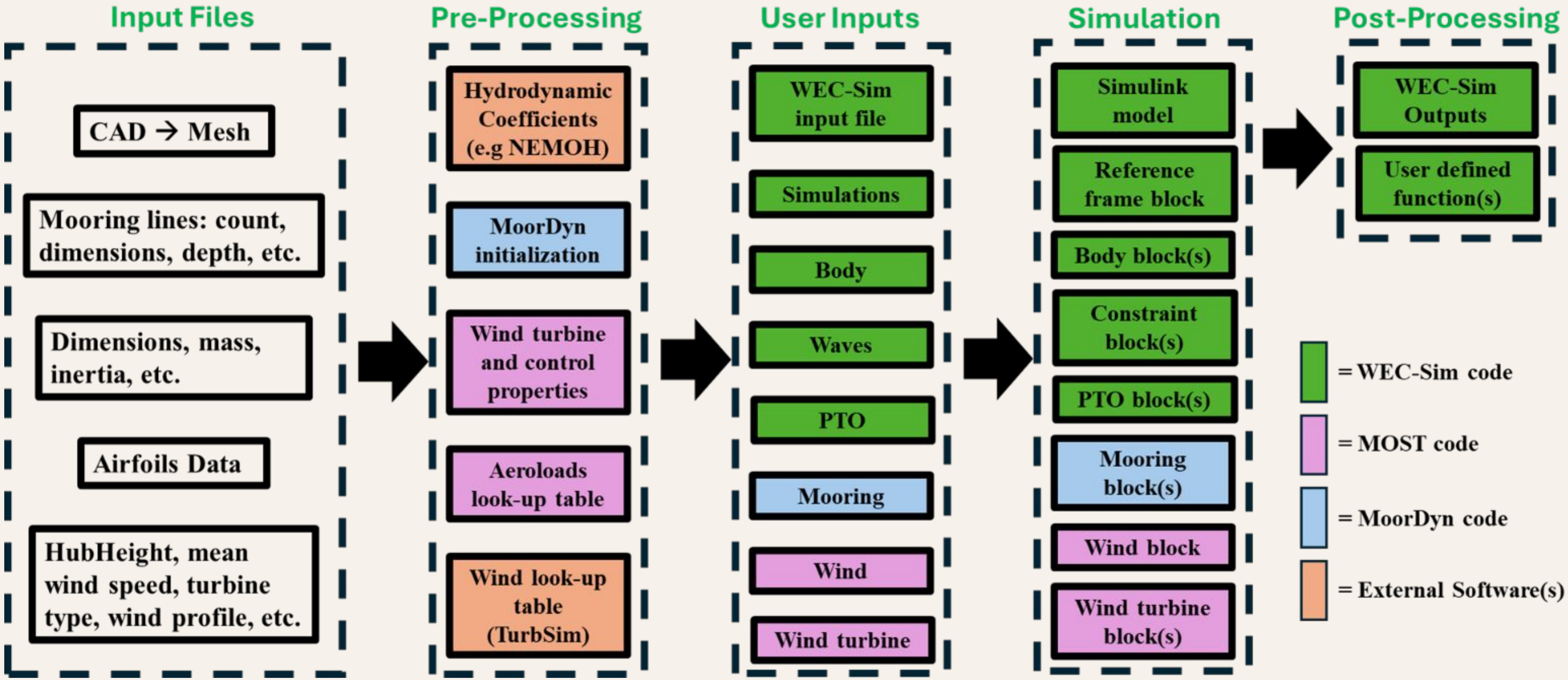
[14] McCabe, Khanal, & Haji. 2024. *UMERC*. doi: 10.5281/zenodo.14504017

Adjusted float design

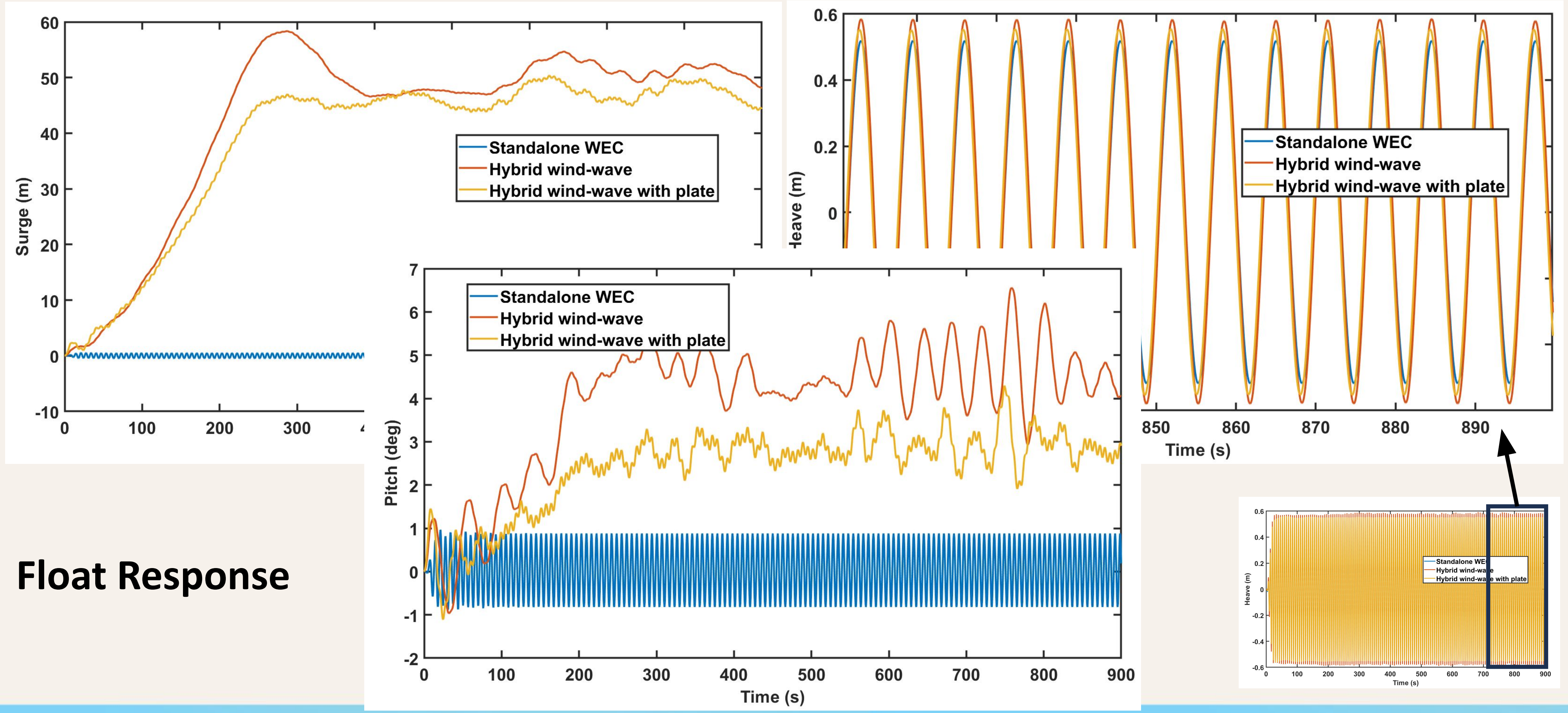
- Adjusted float dimensions to integrate with the WTs and align natural frequency with predominant wave frequency at the target site.
- Rated power kept at 286 kW, same as in original RM3.
- Design of experiments to investigate impact of design variables on float natural period: parameter study (4 factors, 3 levels each, tapered height) - 9 simulations.
- Factors: outer diameter, inner diameter, height, draft.
- Base level was the float in RM3
- To increase the natural period of the float:
  - Outer diameter: increase
  - Inner diameter: decrease
  - Height: increase
  - Draft: increase
  - Tapered height: decrease



Framework: WEC-Sim+MOST+MoorDyn

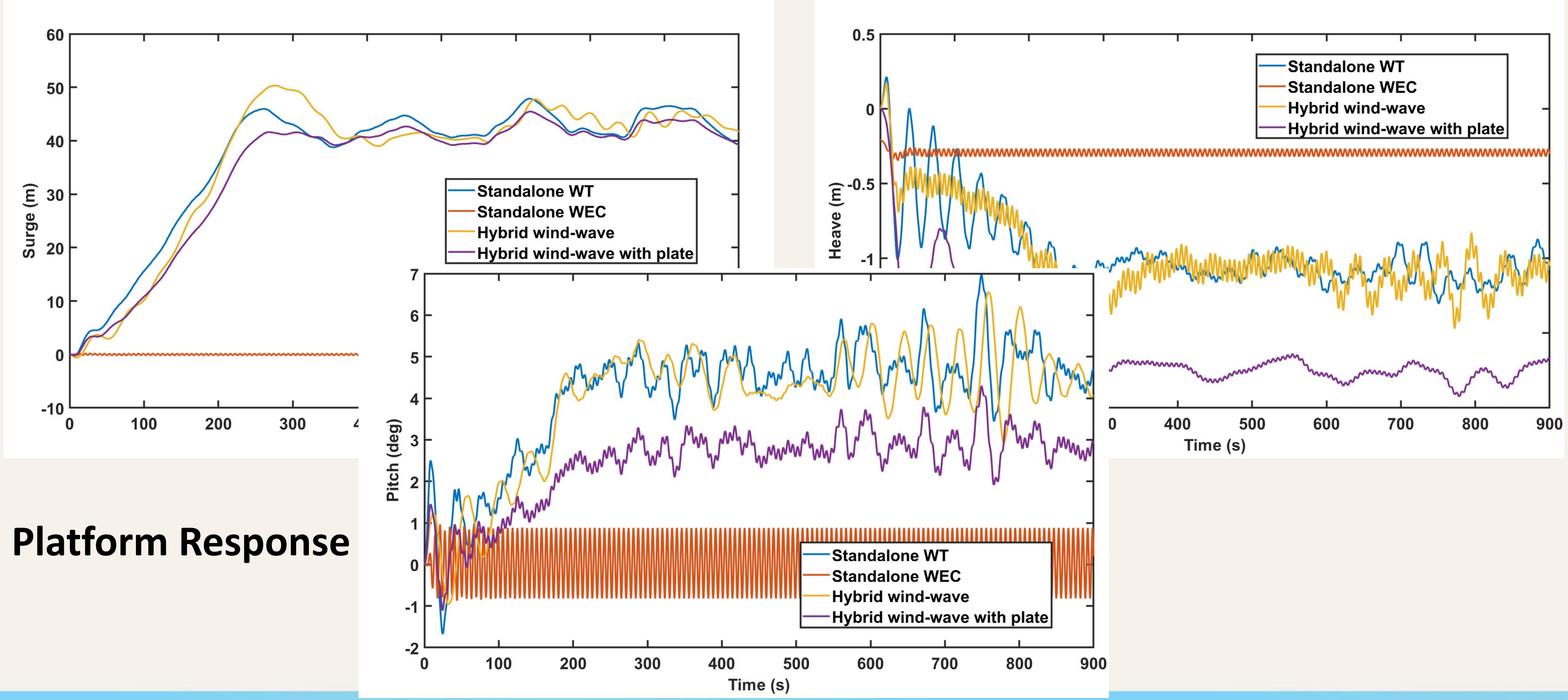


Results: 5MW WT + Float + Spar platform (6.5s, 1.75m, regular)



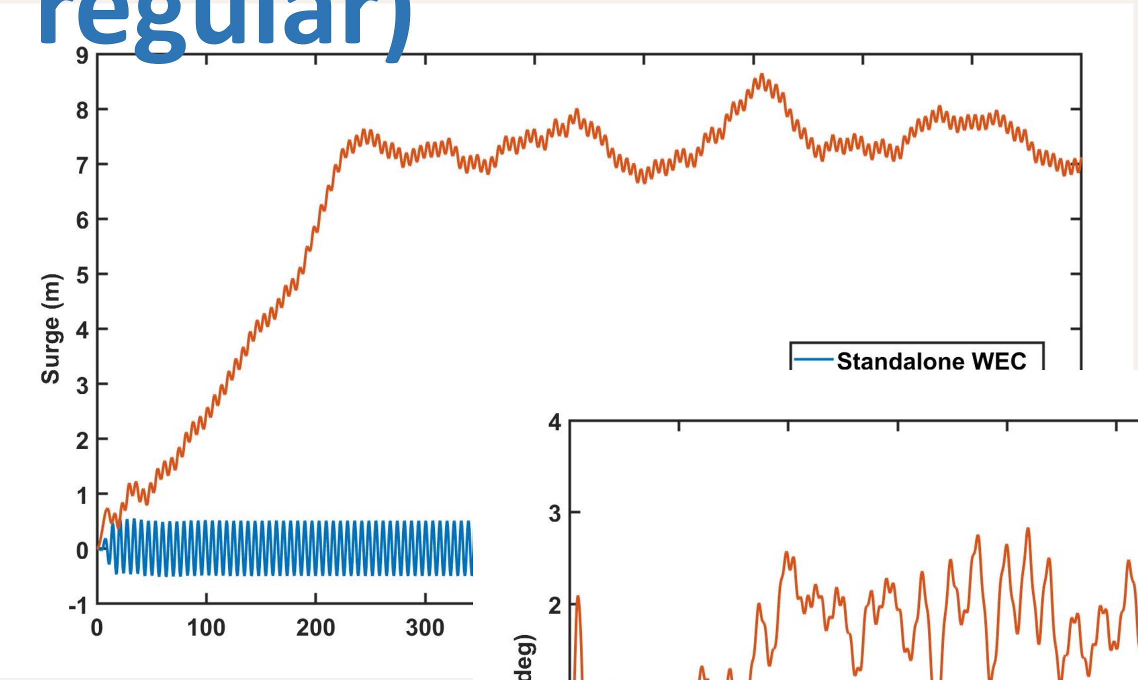
Float Response

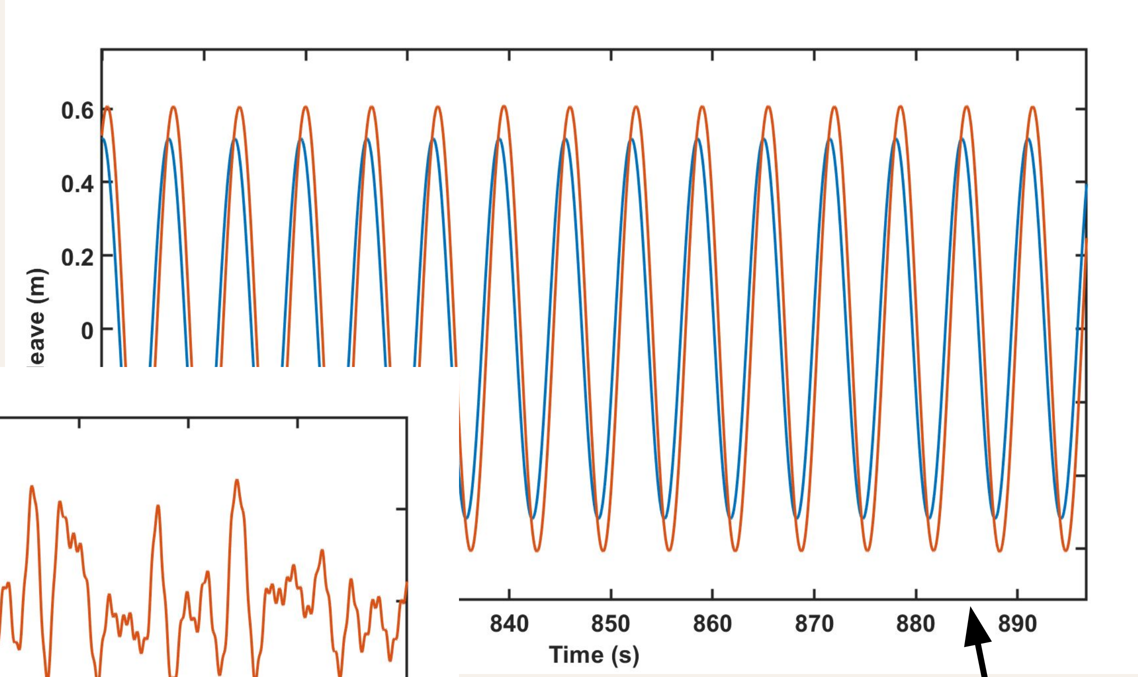
Results: 5MW WT + Float + Spar platform (6.5s, 1.75m, regular)

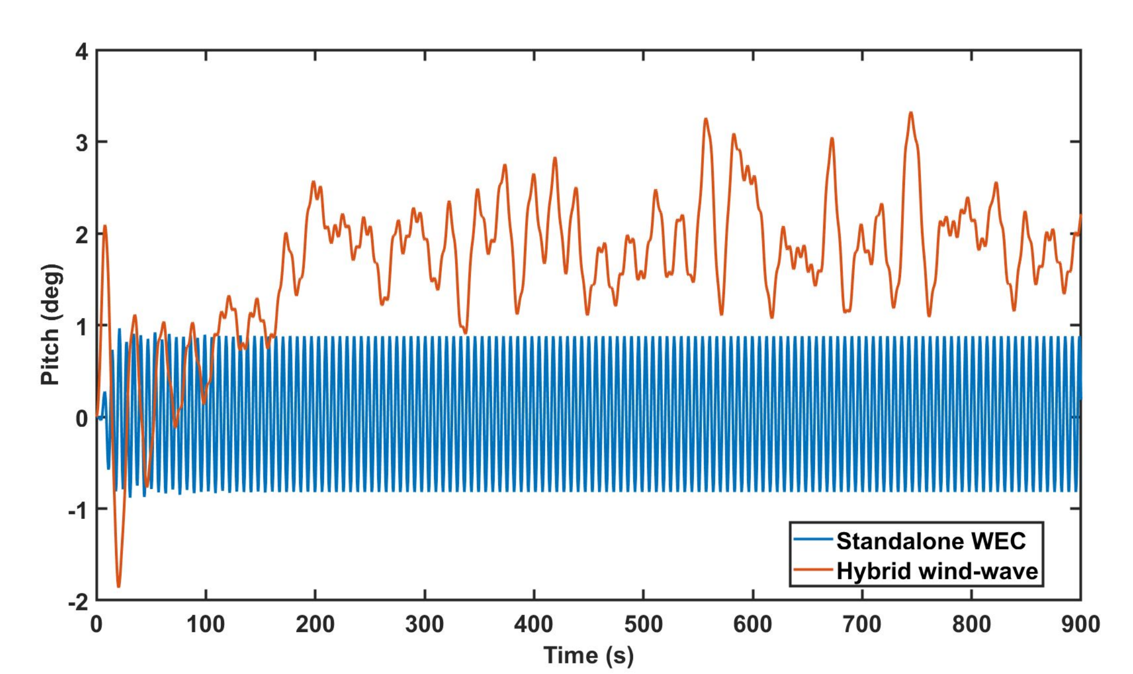


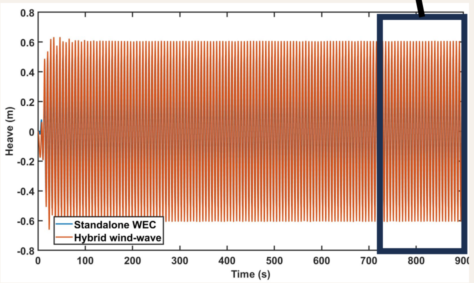
Platform Response

Results: 5MW WT + Float + Semi-submersible platform (6.5s, 1.75m, regular)









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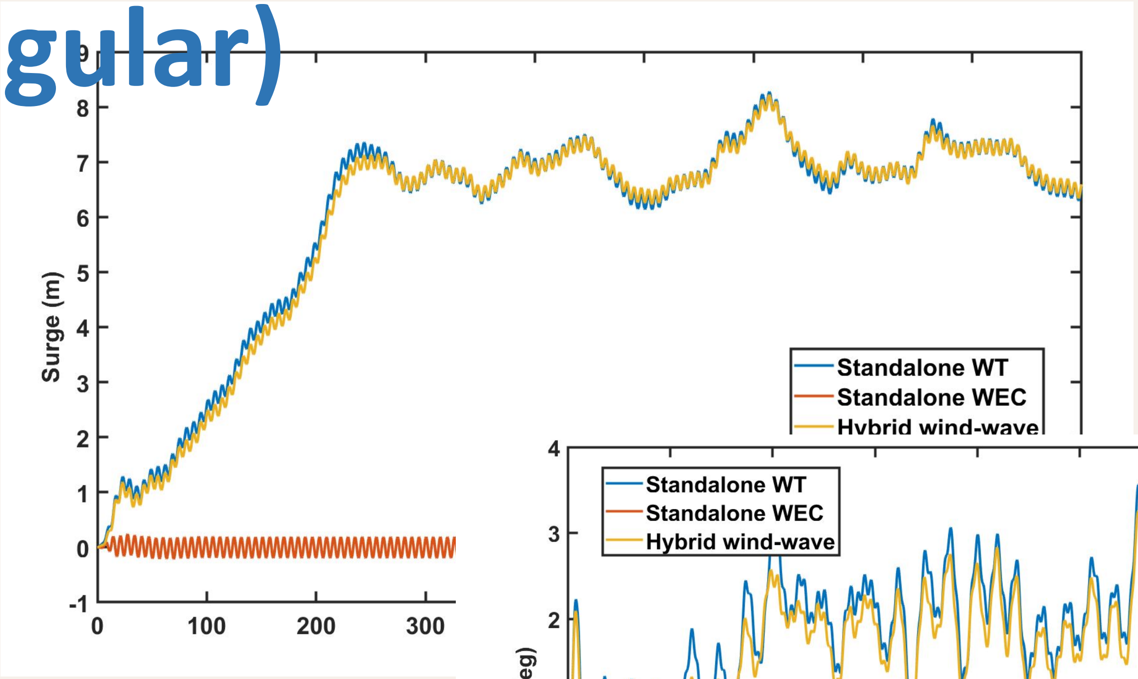

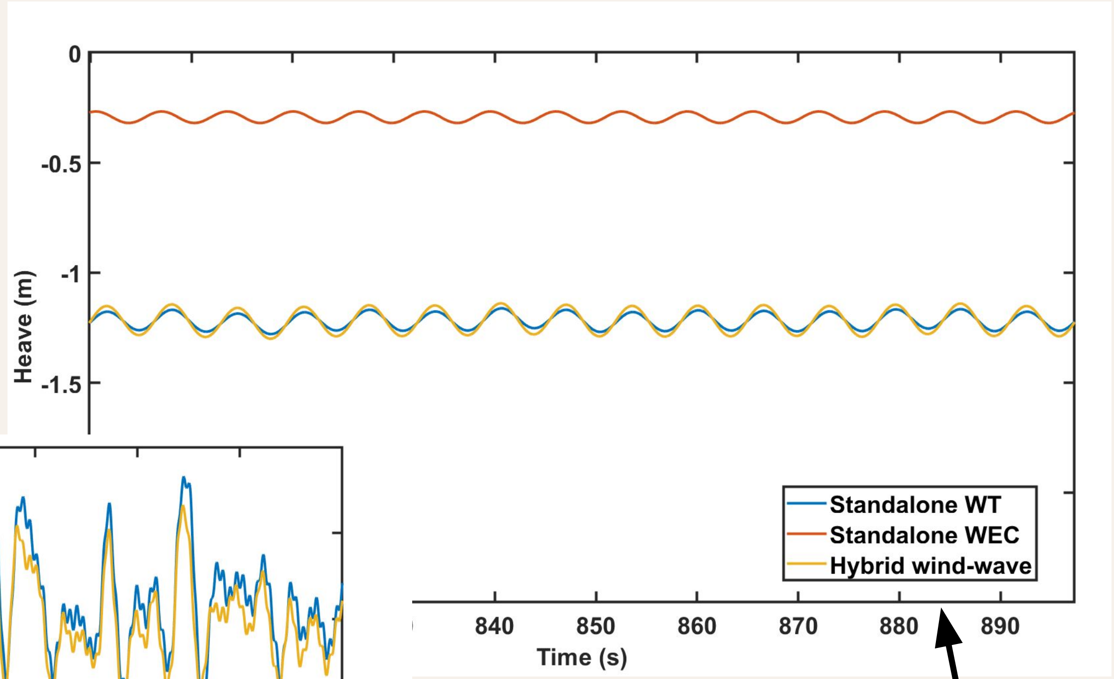

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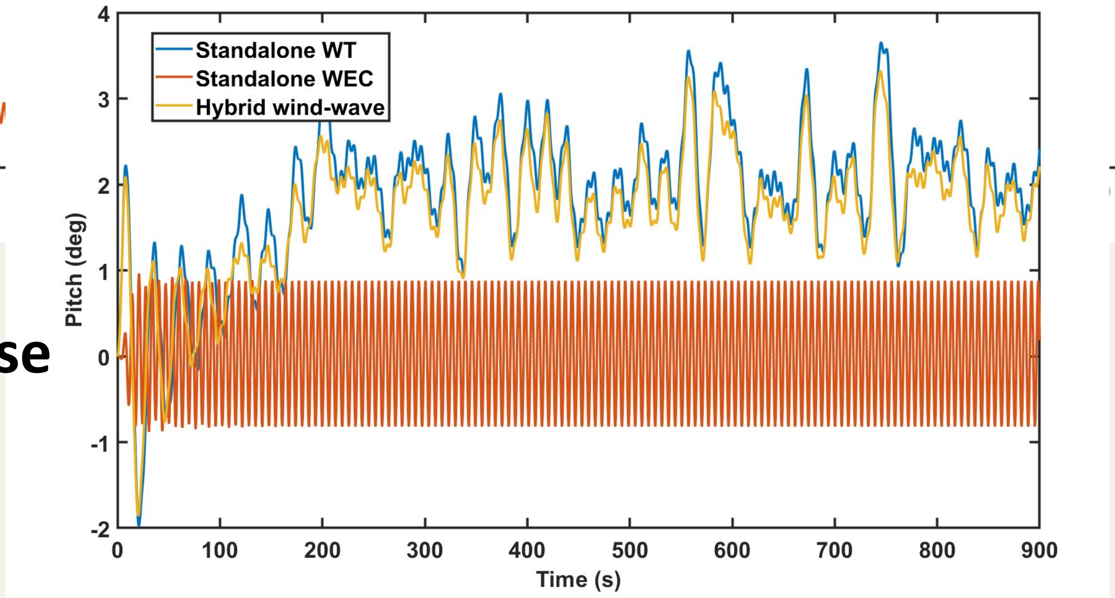
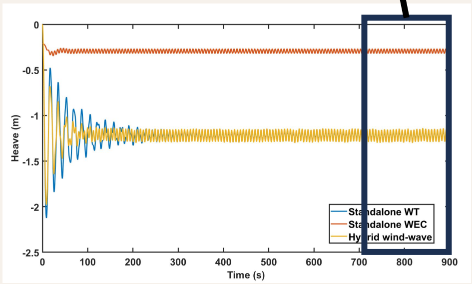
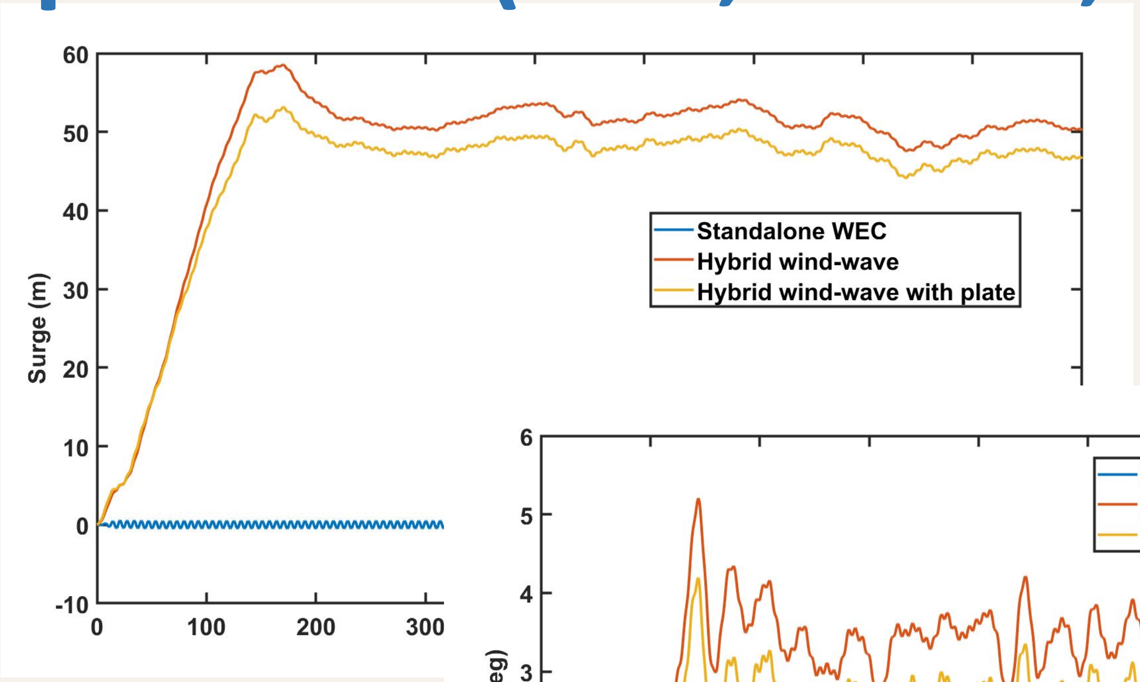
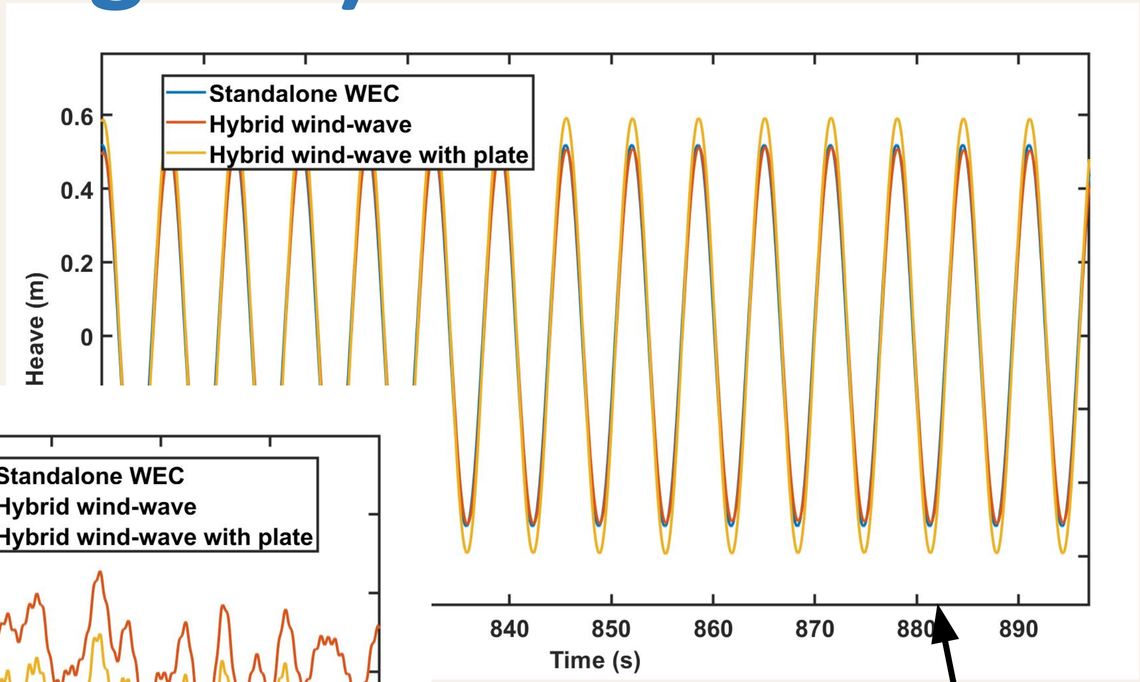
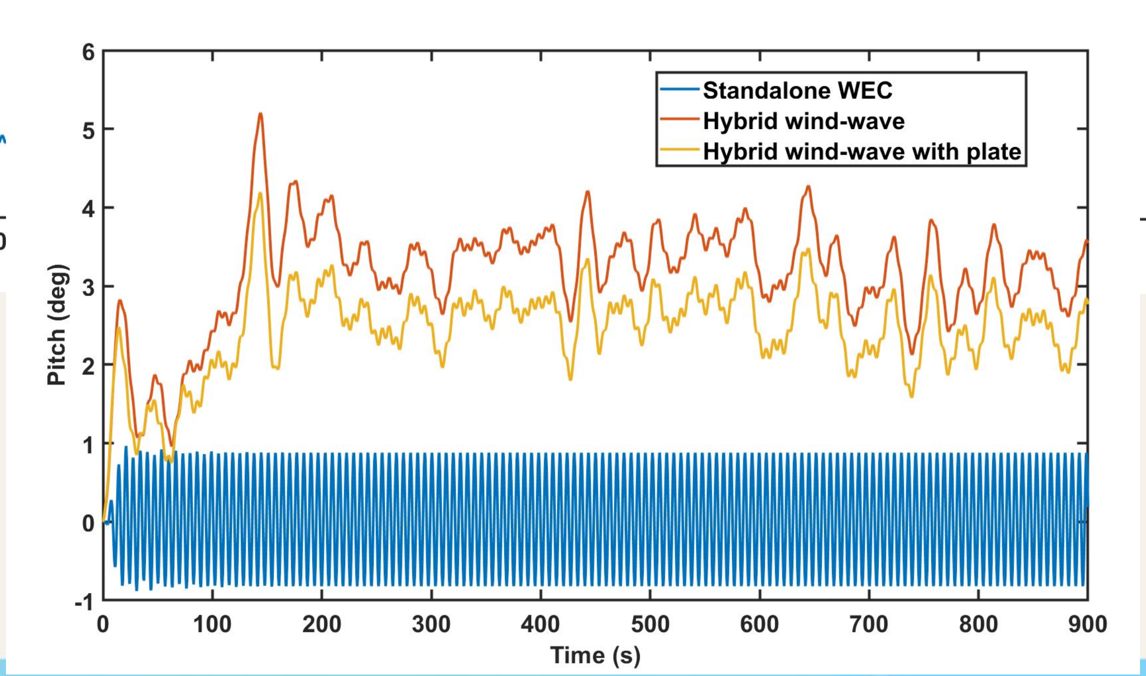


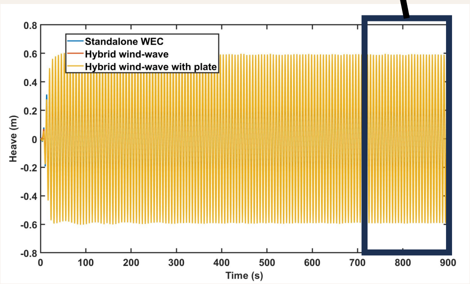


Results: 15MW WT + Float + Spar platform (6.5s, 1.75m, regular)









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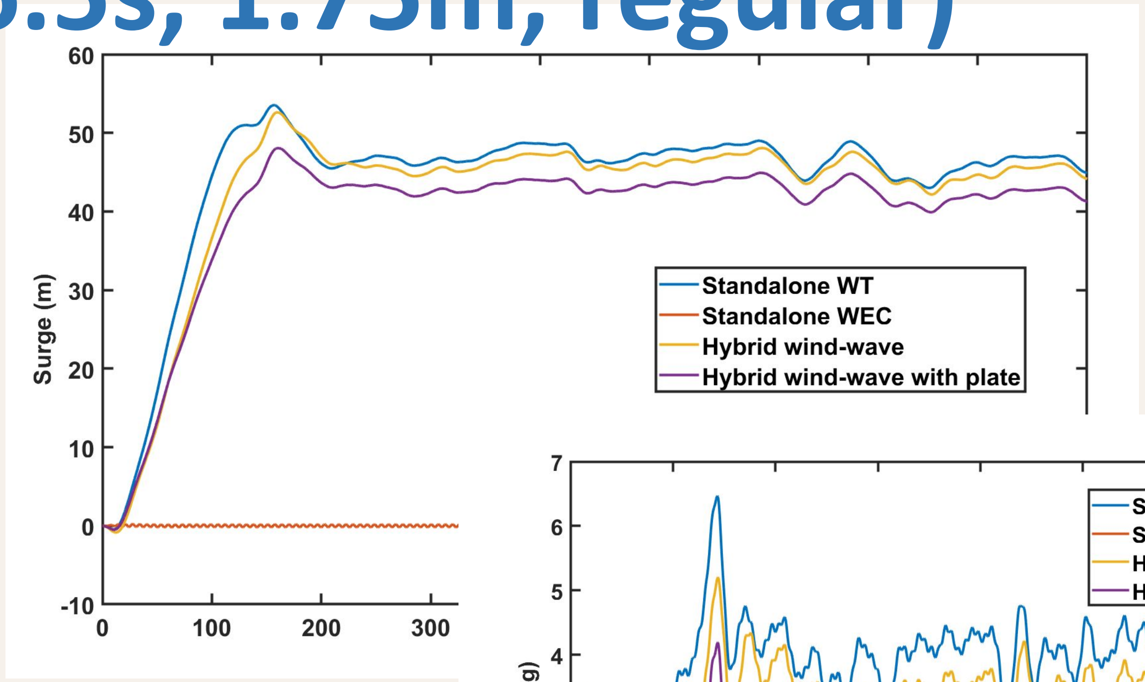

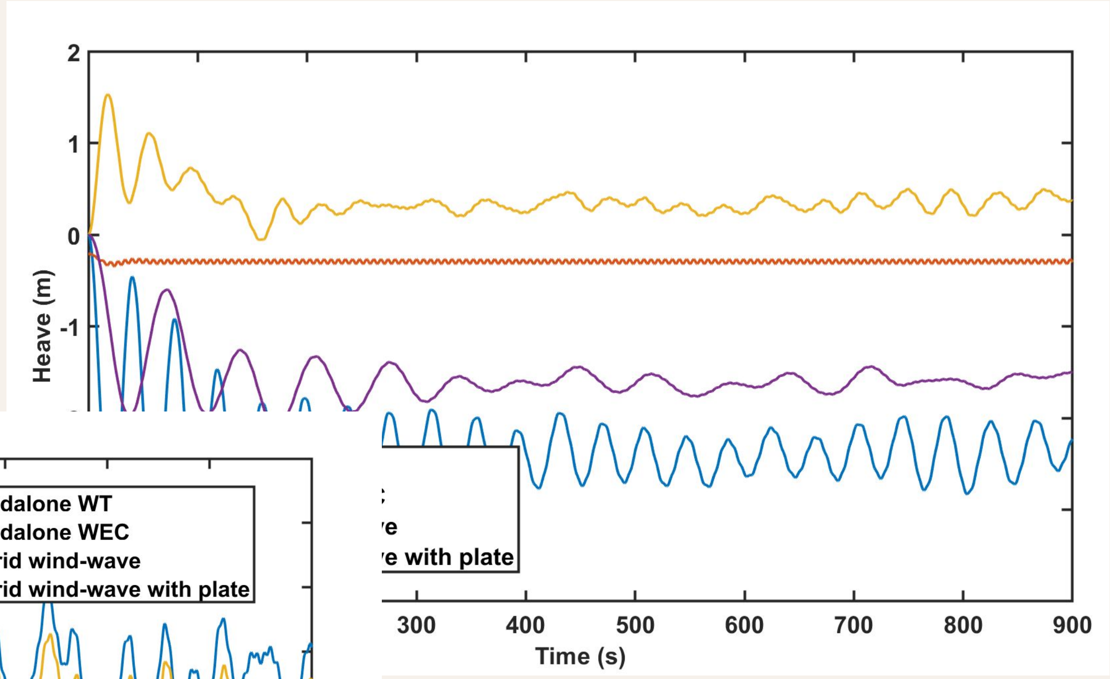

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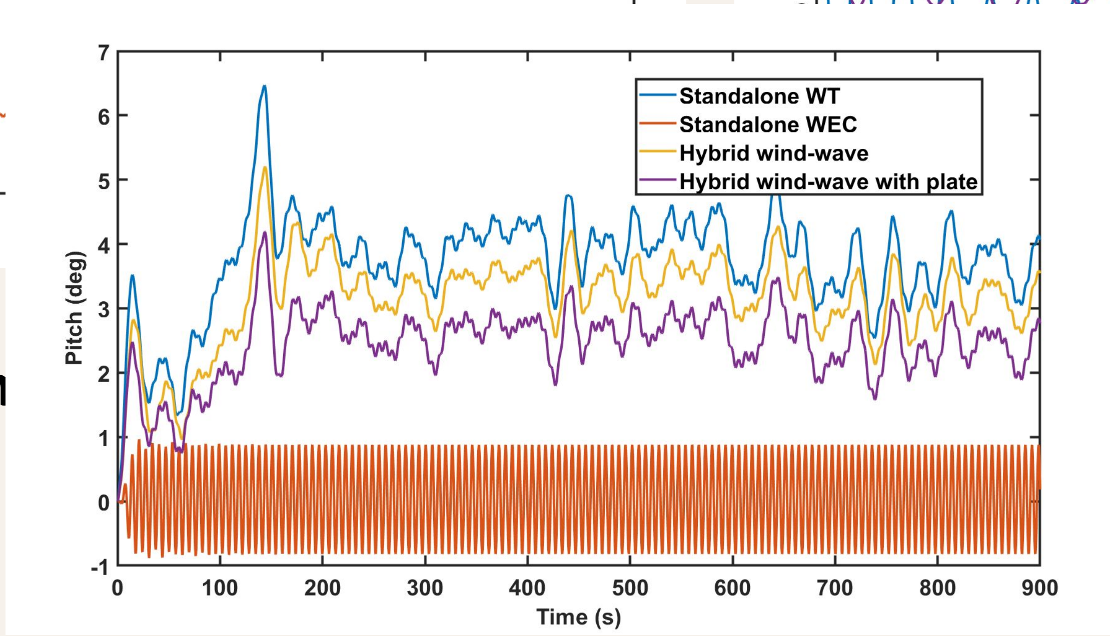

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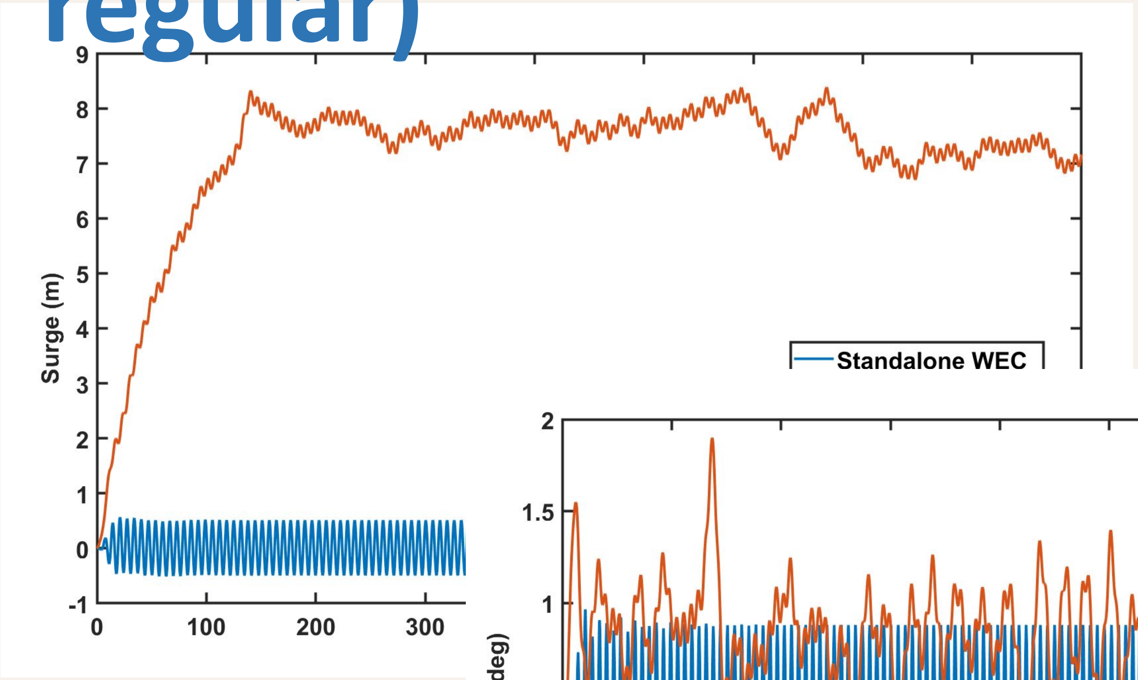

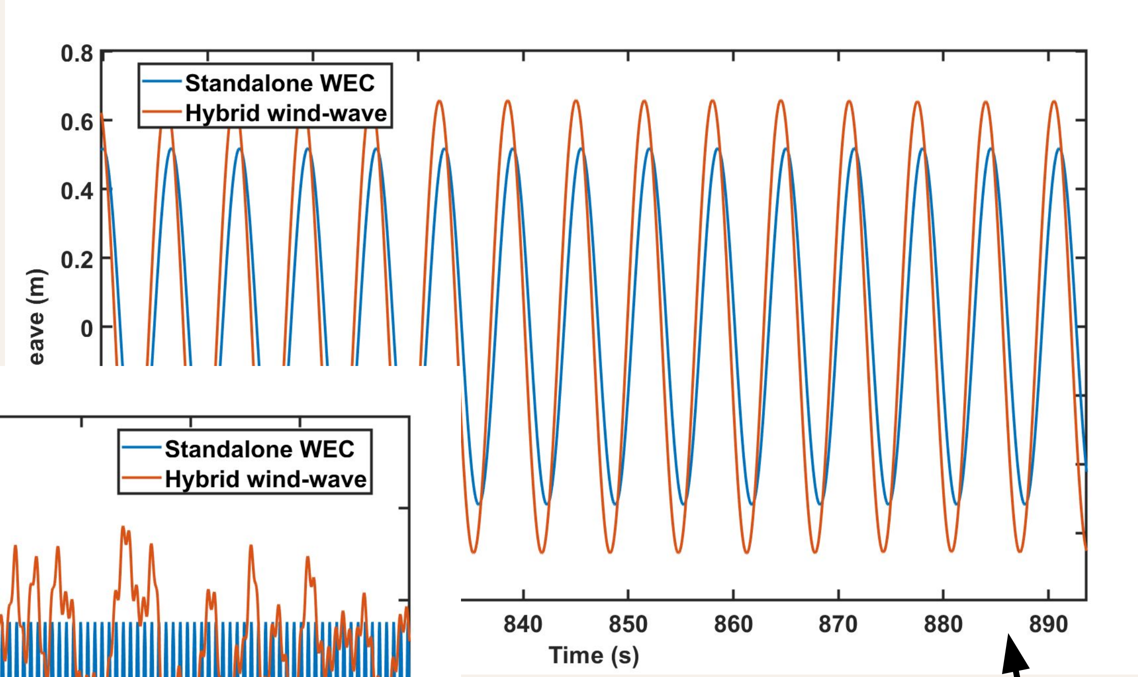

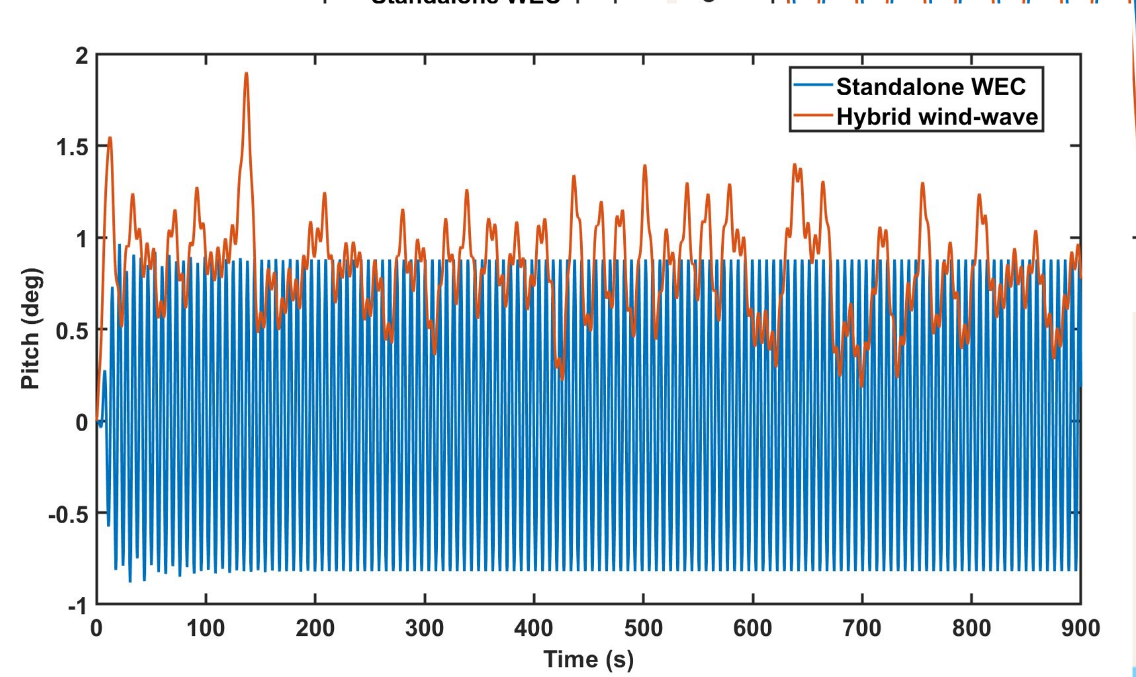

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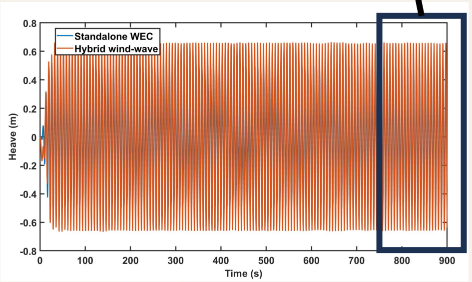

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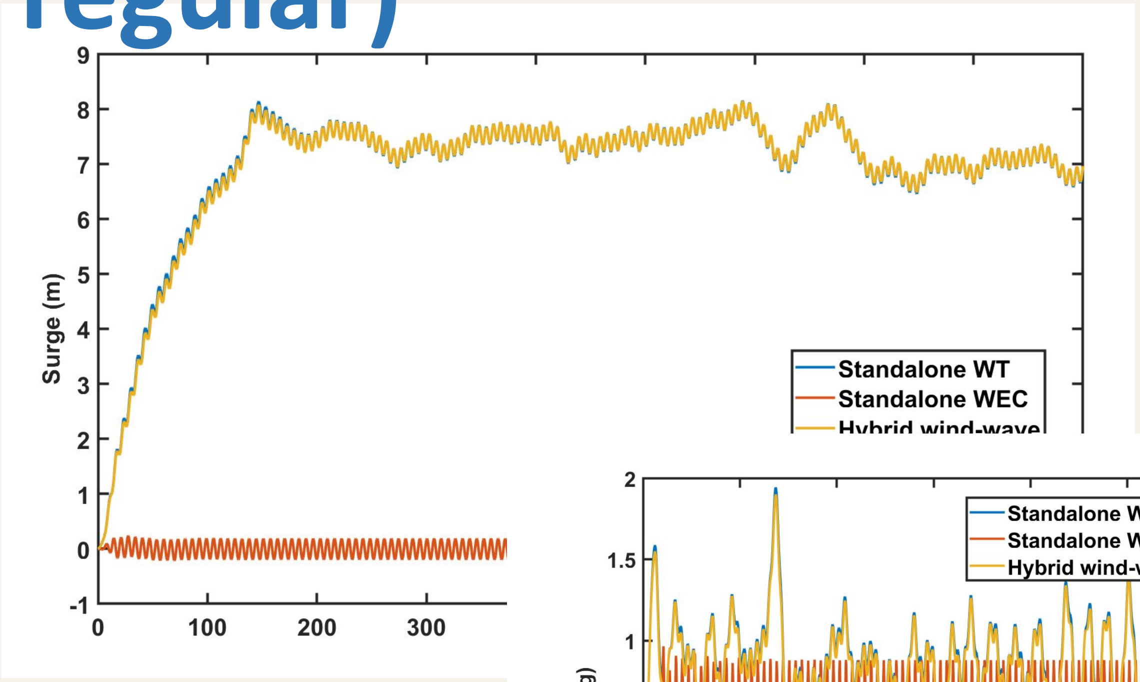

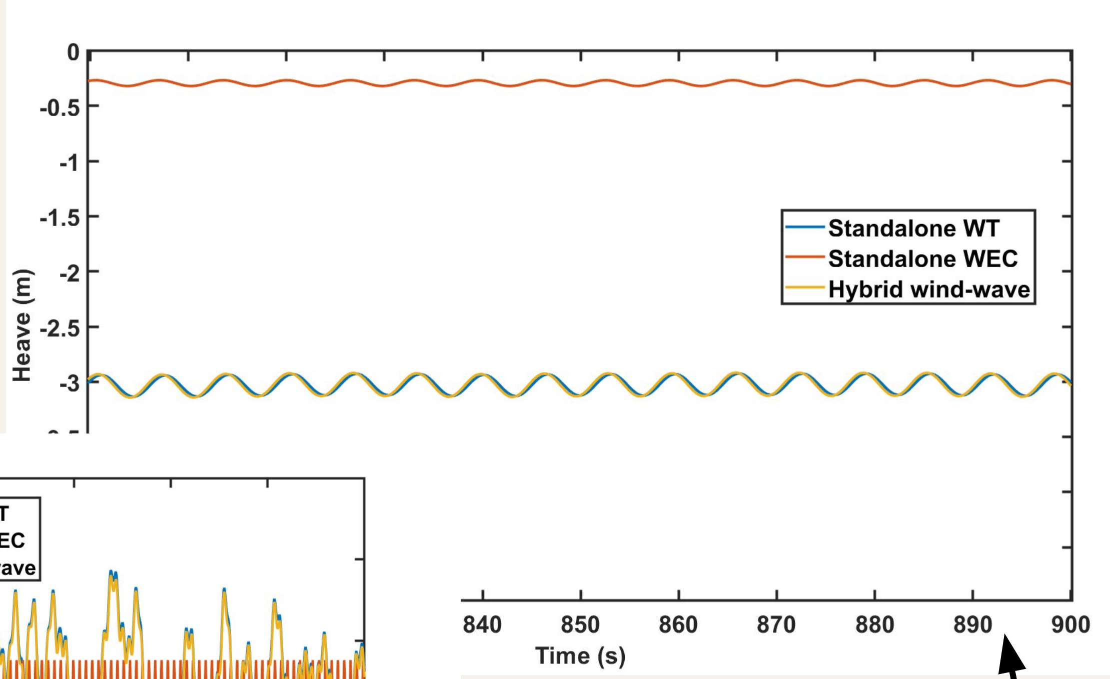

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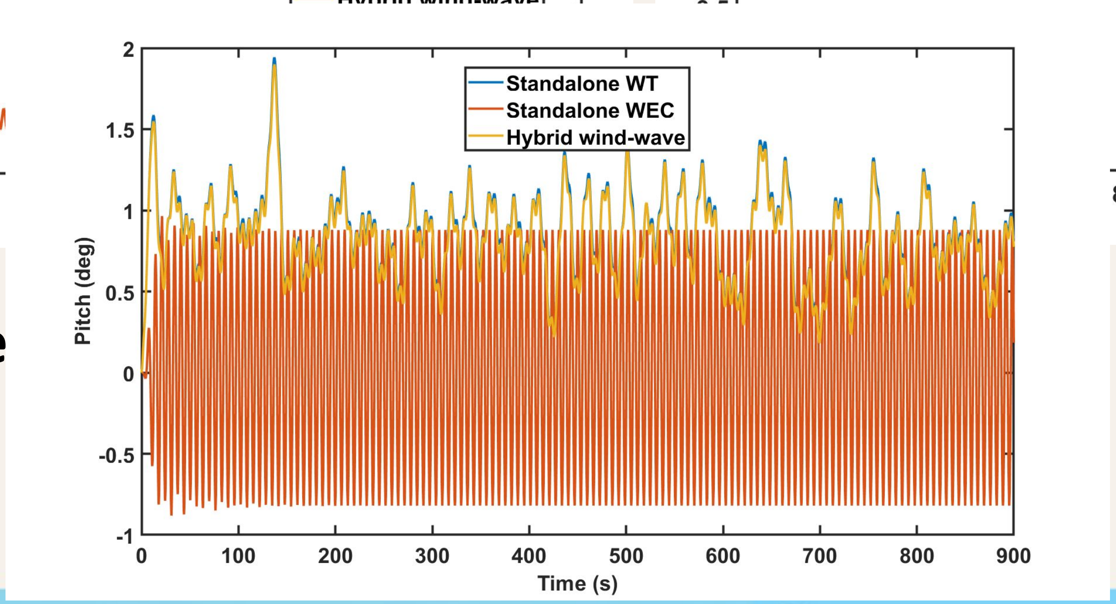

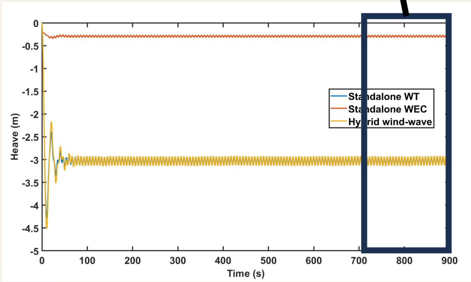

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