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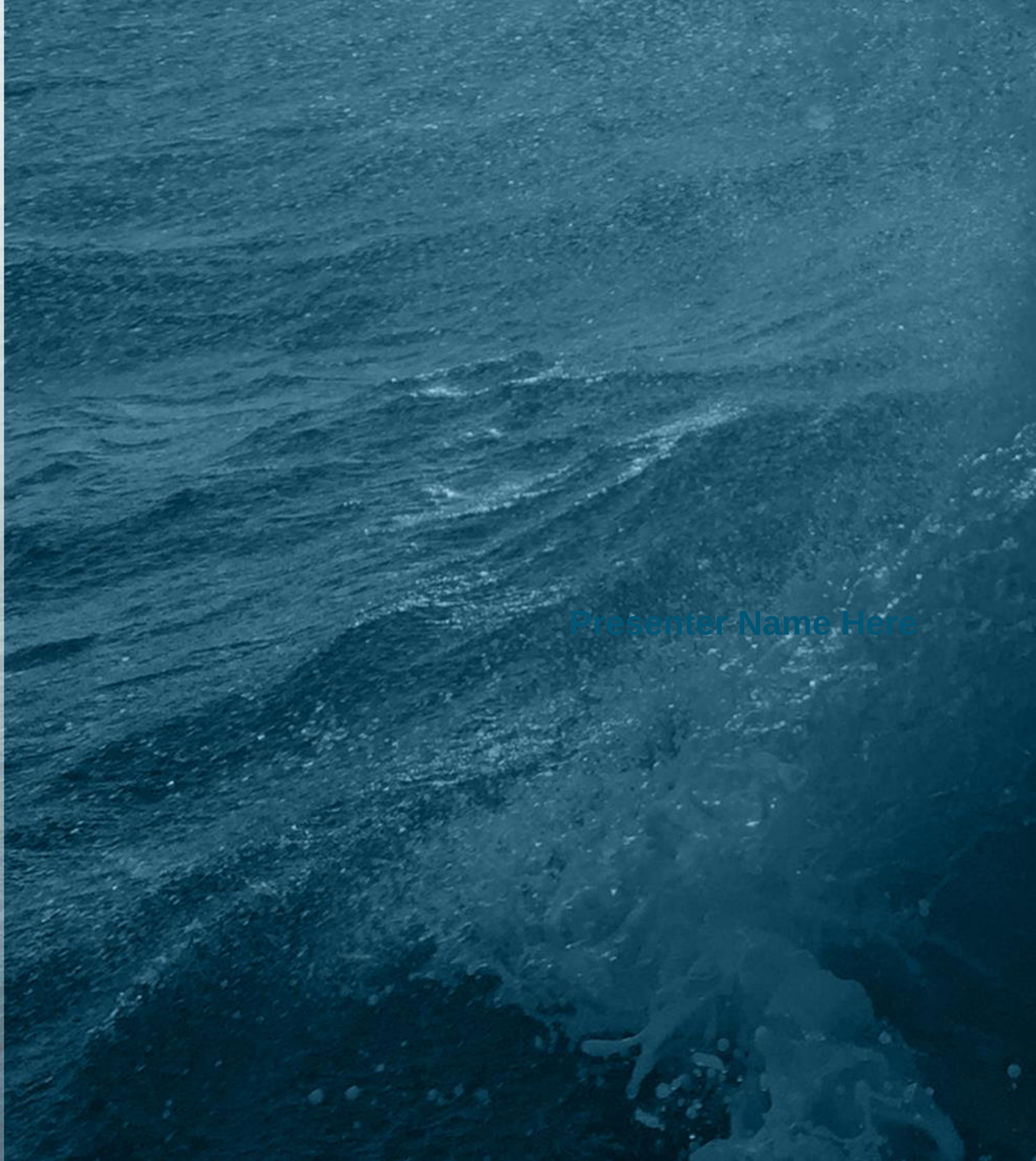
Optimal Power Flow in Marine-Enhanced Grids Integrating Offshore Wind and Wave Energy

Kevin Wyckoff
Javad Khazaei
Faegheh Moazeni
Arindam Banerjee



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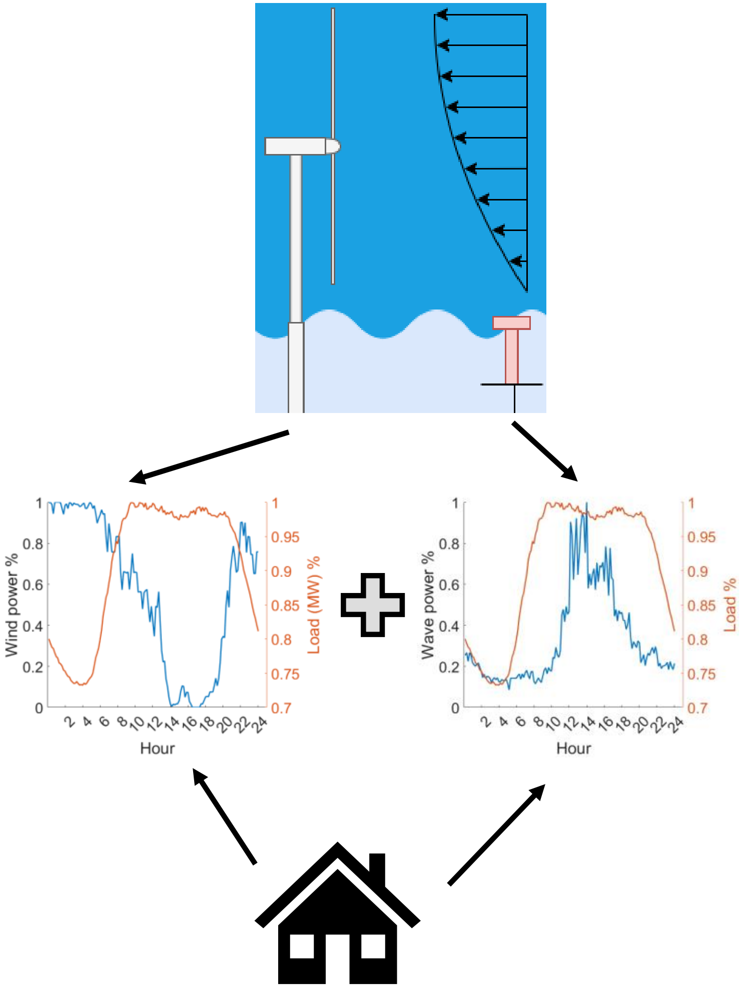
Integrating offshore energy into grids



- **Variability**
  The wind and waves are not controllable, and the amount of available energy changes in time, in contrast to a conventional generator whose maximum power output is always the same.

- **Balancing demand and supply**
  Grid operations involve balancing demand and supply of power. Adding more energy sources with time-varying maximum powers makes achieving this balance optimally, more complicated.

- **Co-locating resources**
  Placing multiple sources of energy in the same location could lead to a more stable power output, depending on when energy is available from each resource. We will investigate grid integration of a co-located wind/wave farm on the east coast of the United States.

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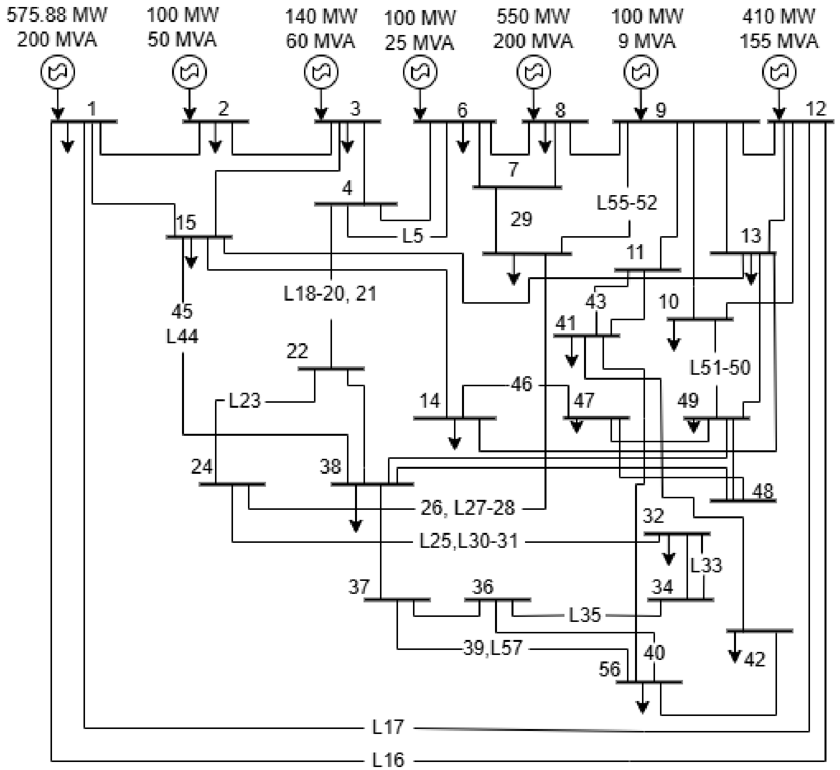
Grid operations with wind and wave

- **Quantifying our system's performance**
  For our system we need to ensure loads are met, select the generator operations, and analyze losses.
- **Optimal Power Flow (OPF)**
  Simulate a grid as a series of buses (nodes) connected by branches (lines), with buses having generators, loads, or neither. A cost function is used to find an optimal set of generator outputs, and the voltage states at the buses are also found, with losses along lines calculated.
- **Solving the OPF gives us a picture of operating a grid**



An example system, the IEEE 57 bus system, with nodes, lines, and generators shown

How well do wave energy converters (WECs) compliment offshore wind turbines (OWTs) when integrating into the grid?

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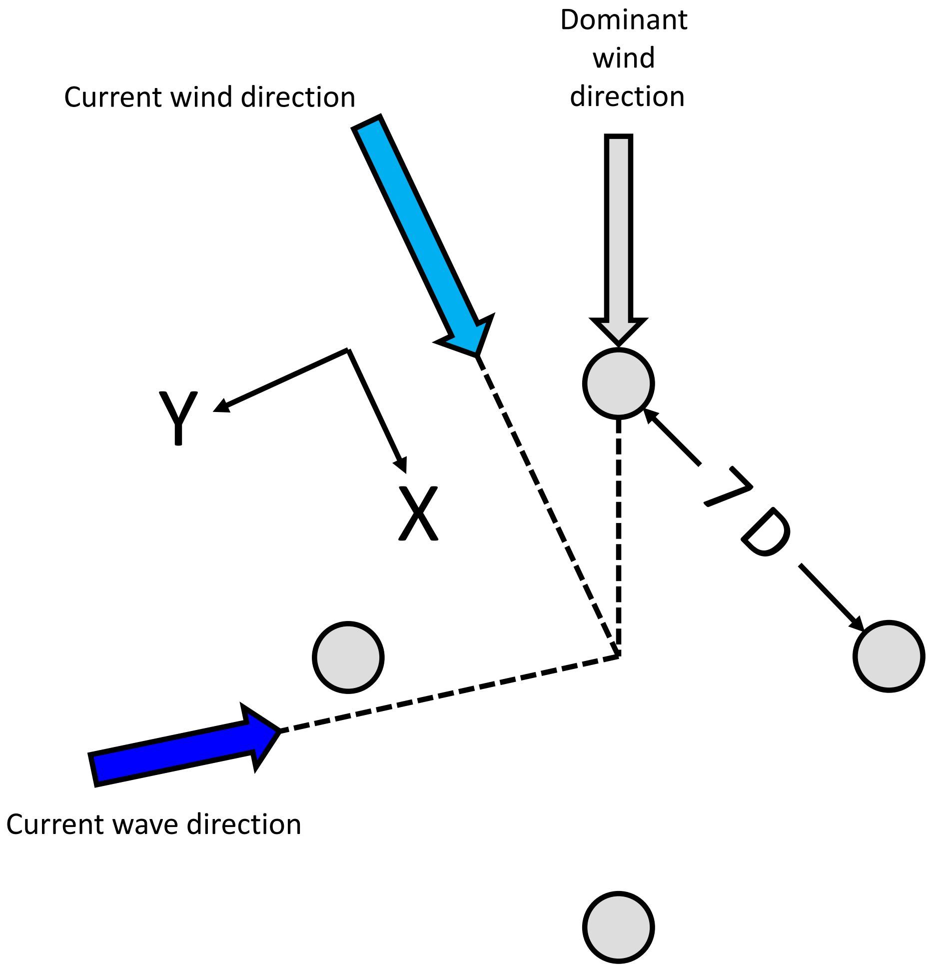
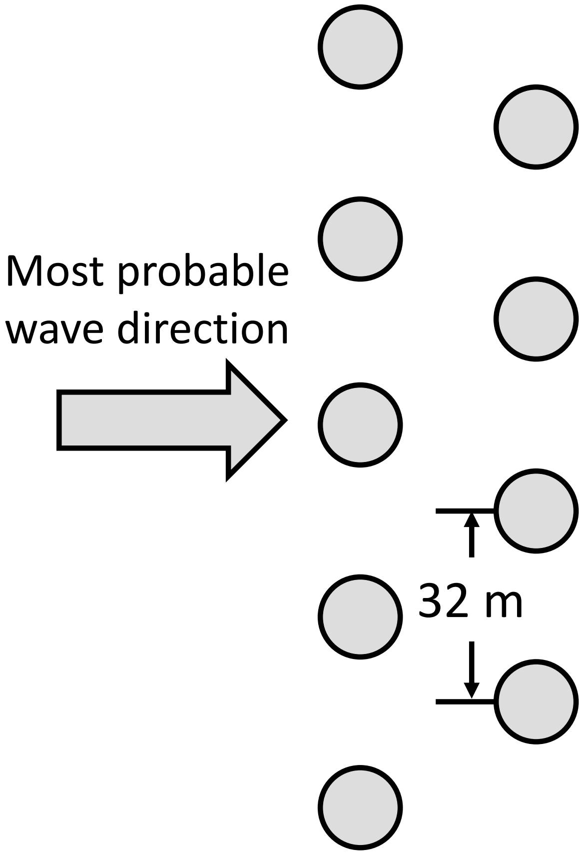
Modeling OWTs

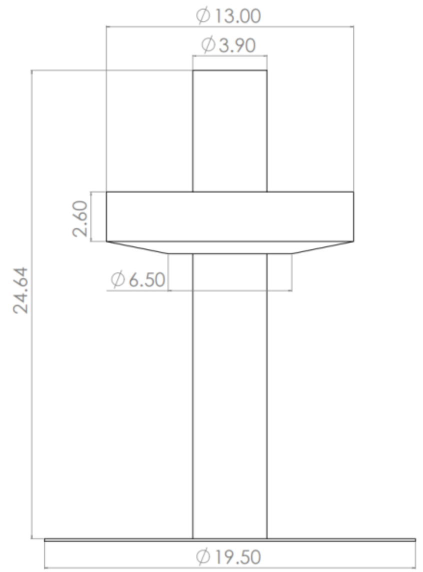
- **FAST.Farm**
  Low fidelity multi-physics code for simulating OWTs developed by NREL
  4 NREL 5 MW OC3 reference turbines 7 D apart
  151 x nodes, 141 y, 30 z with 10 m spacing
  The number of turbines was limited for computational reasons
- **TurbSim inflow**
  IEC Kaimal 61400-1
  Turbulence Intensity: 7%
  Wind profile - power law exponent: 0.2
  10 m spacing, 200 points in y, 35 in z, 0.01s time resolution
  Wind inflow files are generated in 0.5 m/s increments and the recorded wind speed is binned to determine which inflow file is used



Modeling WECs

- **Scaled RM3**
  To fit into shallower continental shelf waters, the RM3 (reference model 3) WEC is scaled down by 1.5 times
  Two body heaving point absorber
  RM3 model is compared to performance reported by Sandia National Labs
- **Models**
  ANSYS AQWA boundary element method code generates hydrodynamic coefficients
  WECsim simulates point absorber dynamics in time domain, including power production
- **Farm configuration**
  9 WECs were simulated in an array with 2 rows with a 32 m spacing in the perpendicular to the most probable direction





The scaled RM3 point absorber

AC OPF problem formulation

Quadratic cost function for conventional generators

Linear cost for wind/wave farm

Only the wind and wave available powers change in time

$$\min_{x_t}\left(\sum_{g=1}^{7} a_g P_{g,t}^2 + b_g P_{g,t} + c_g\right) + k_{ww} P_{ww,t}$$

$$subject\ to$$

Nodal power balance

$$g(x_t) = 0$$

Flow limits

$$h(x_t) \le 0$$

$$x_{min,t} \le x_t \le x_{max,t}$$

Real and reactive powers of generation units

$$x = \begin{bmatrix} P_{g,t} \\ Q_{g,t} \\ V_{i,t} \\ \theta_{i,t} \end{bmatrix}$$

Bus voltage magnitude and phase

$$P_{g,max} \neq P_{g,max}(t)$$

$$P_{ww,max,t} = P_{wind,max,t}(t) + P_{wec,max,t}(t)$$

$$0 \le P_{g,1} \le P_{g,max}$$

$$Q_{g,min} \le Q_{g,1} \le Q_{g,max}$$

Voltages are constrained to 0.06 per unit

$$0.94 \le V_{i,t} \le 1.06$$

Ramp limits of 20 % are chosen

$$-0.2P_{g,max} \le P_{g,t-1} - P_{g,t} \le 0.2P_{g,max}$$

$$-0.2(Q_{g,max} - Q_{g,min}) \le Q_{g,t-1} - Q_{g,t} \le 0.2(Q_{g,max} - Q_{g,min})$$

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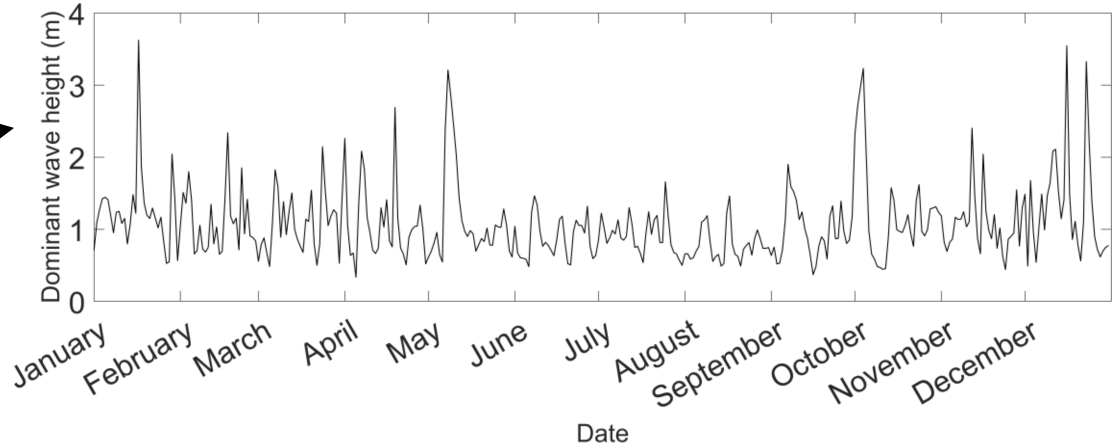
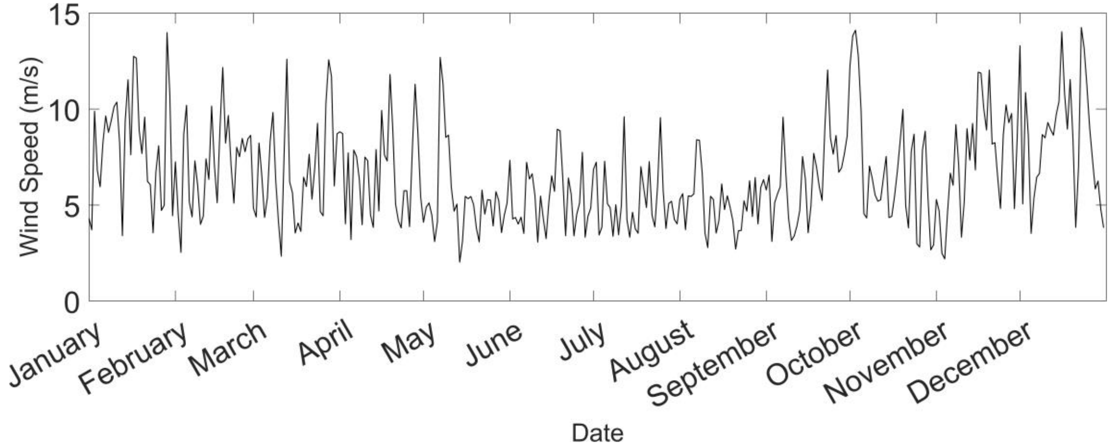
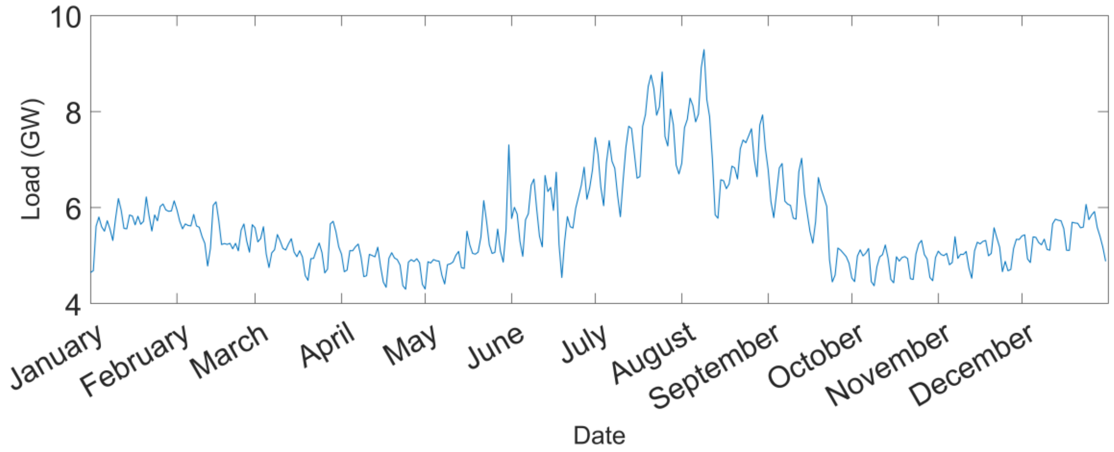
Case Study

- **NOAA buoy provides wind and wave data**
  Buoy 44065 – 15 NM SE Breezy Point NY
  Anemometer at 4 m above sea level reports 8 minute averages every 10 minutes
  Hourly dominant wave statistics
- **Load demand**
  Nearby 10 minute electric load for NY city from NYISO is employed





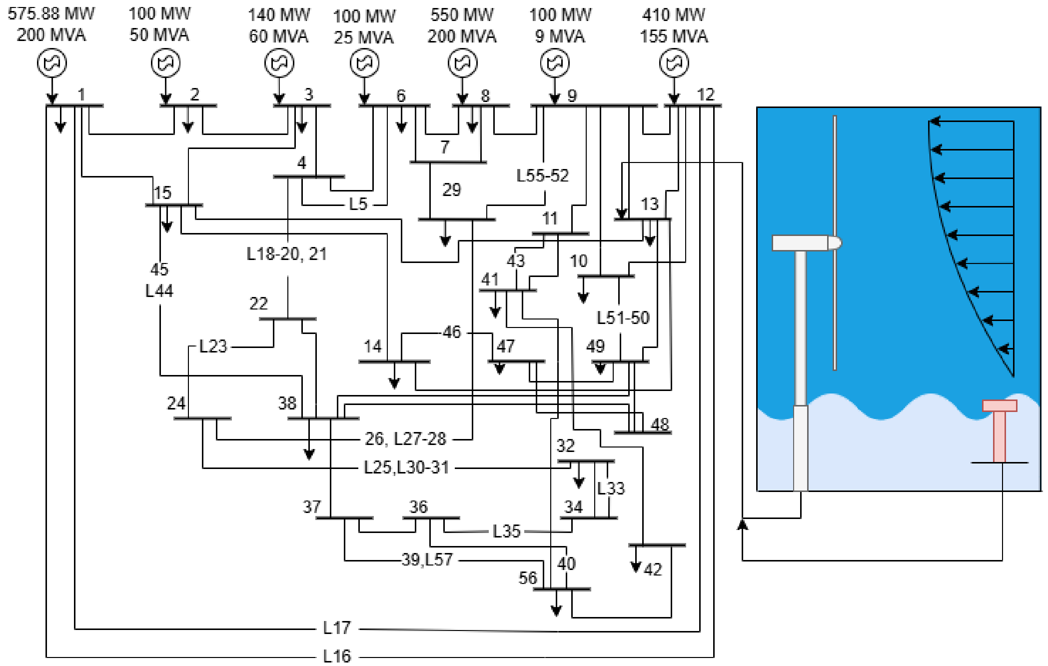


Cost coefficients

Bus #	a ($/(MWhr^2))	b ($/MWhr)	k ($/MWhr)
1	0.00375	2	N/A
2	0.0175	1.75	N/A
3	0.025	3	N/A
6	0.00375	2	N/A
13	N/A	N/A	3.5
8	0.0625	1	N/A
9	1.75	0.0195	N/A
12	0.00834	3.25	N/A

Case Study

- **IEEE 57 bus system**
  7 conventional generator units
  Based on AEC grid in TE and WV last century
- **Available Power**
  1976 MW conventional power
  1251 MW load
- **Scaling**
  Load from NY is scaled such that the mean load in time is 76% of 1251 MW



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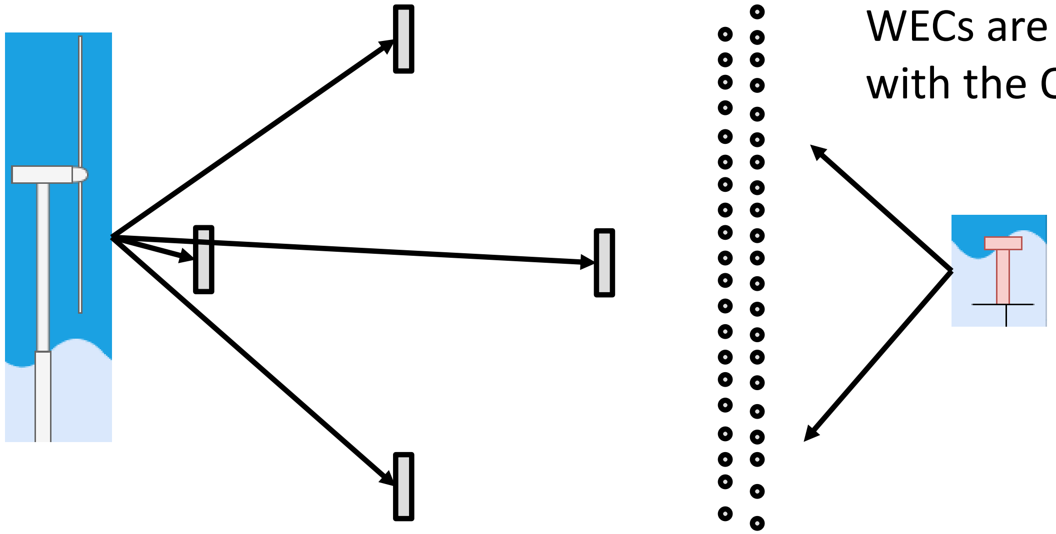
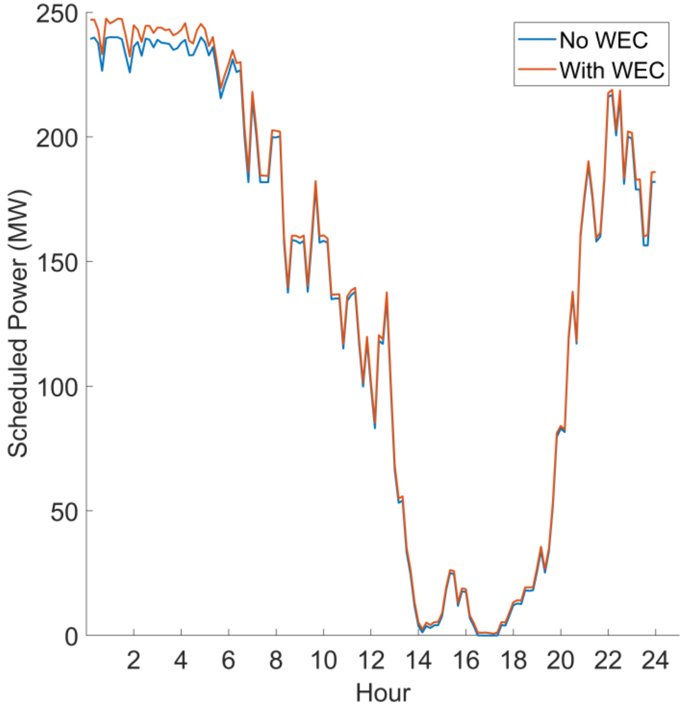
Results – added power

- **April 11 is shown**
  Chosen as a representative day of spring

- **WECs add power**
  The WECs add an average of around 2.9 MW available power (2.1 % of OWT)



We assume 114 WECs are co-located with the OWTs



Scheduled power when the ORE farm is located at bus 13

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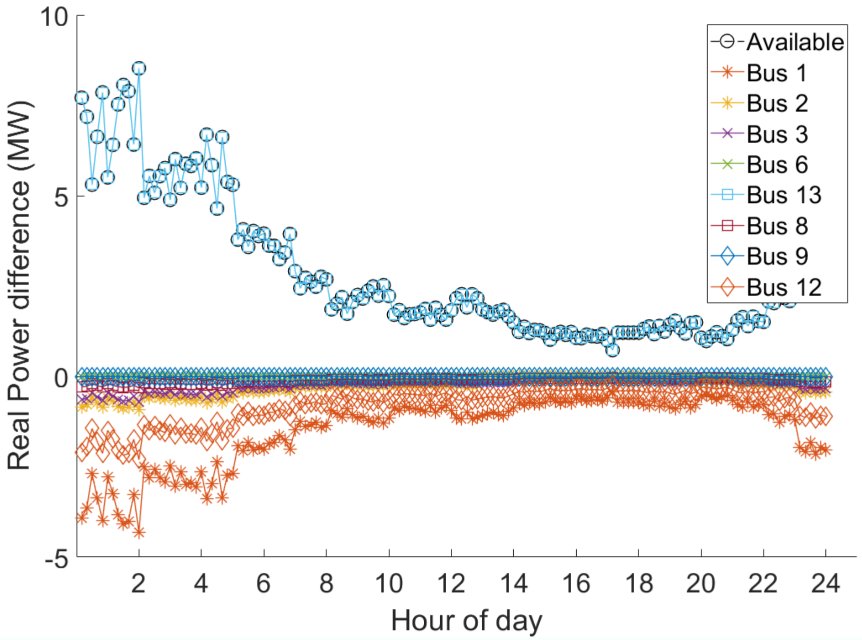
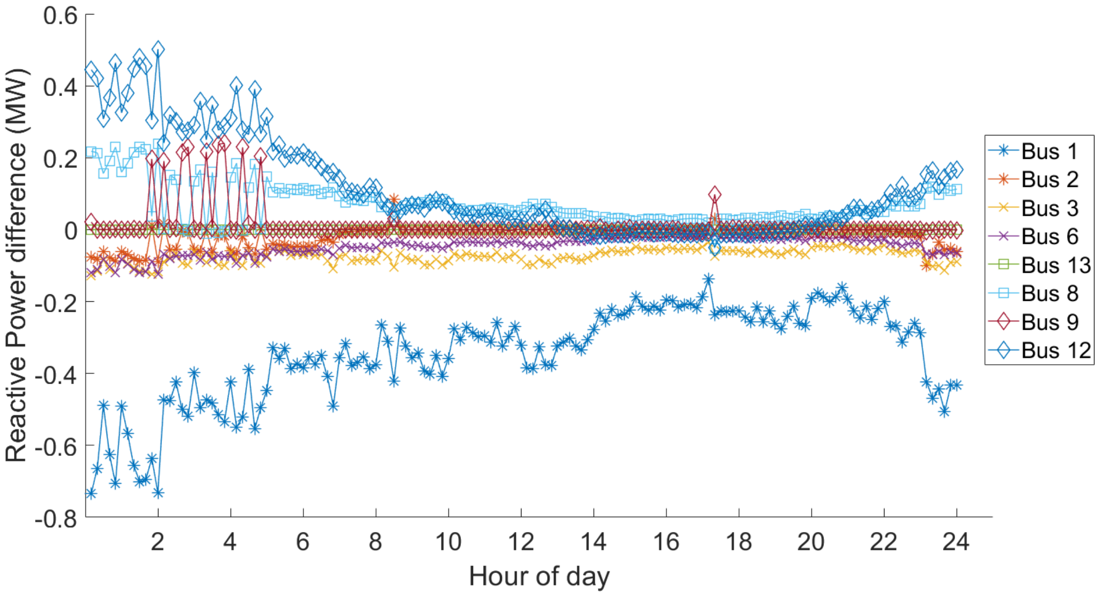
System performance with WECs added

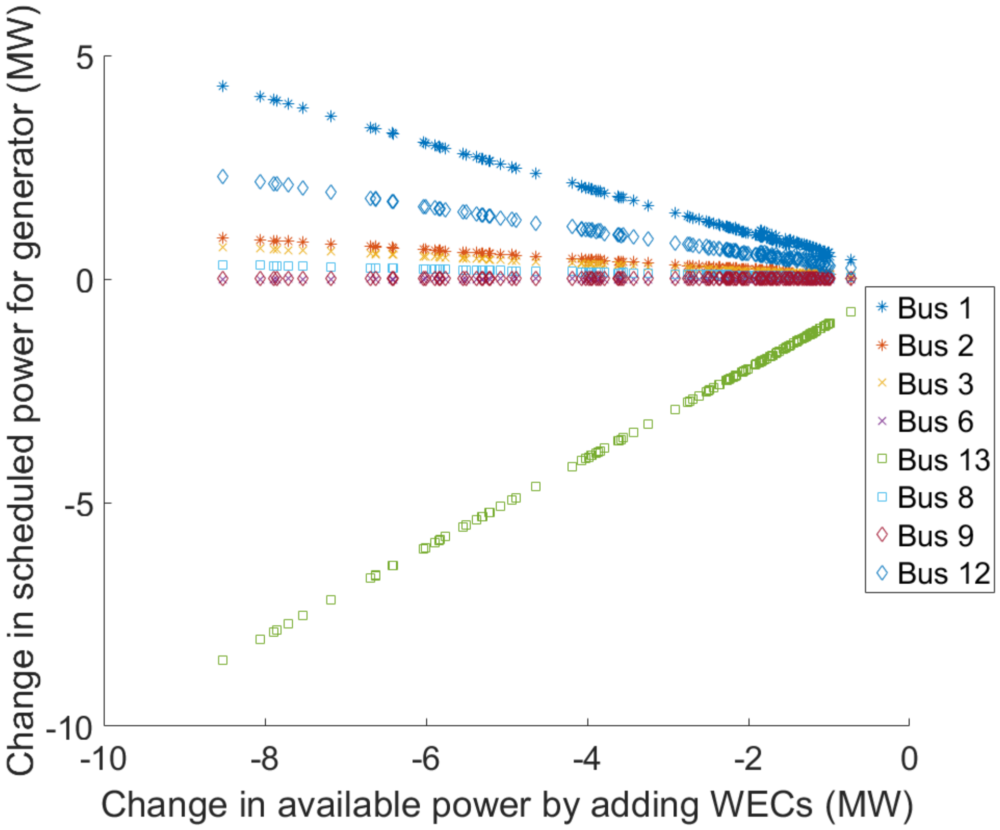
- Scheduled powers follow available power trend
- Power from co-located farm follows exactly the available power
- Bus 1, and other buses see less impact
- Reactive power is effected less

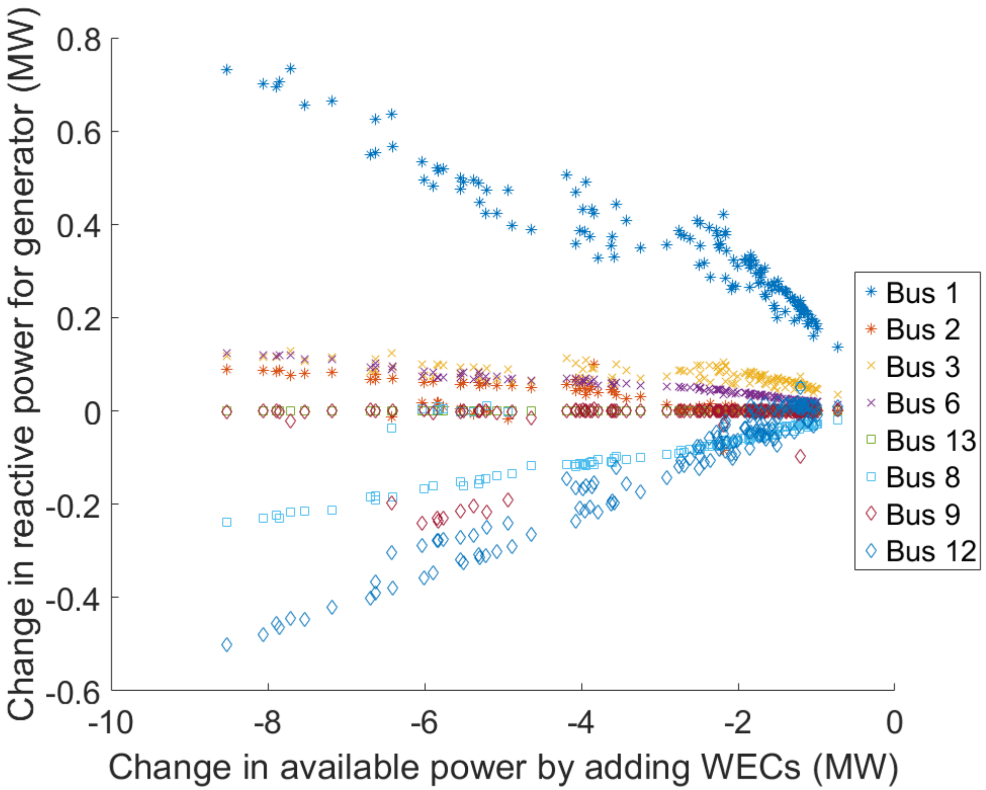




System performance with WECs added

- Real outputs of generators all are linearly related to available power
- Reactive are less well defined as being linear, especially for times with lower available wave energy





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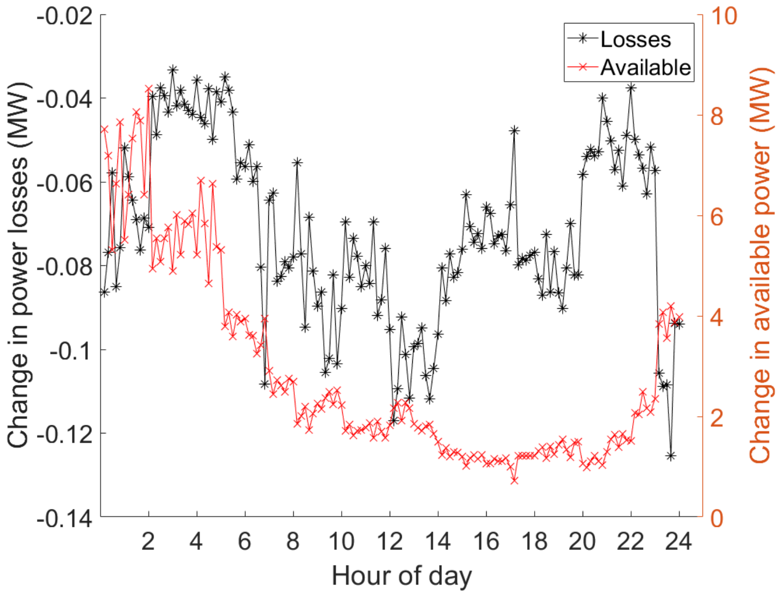
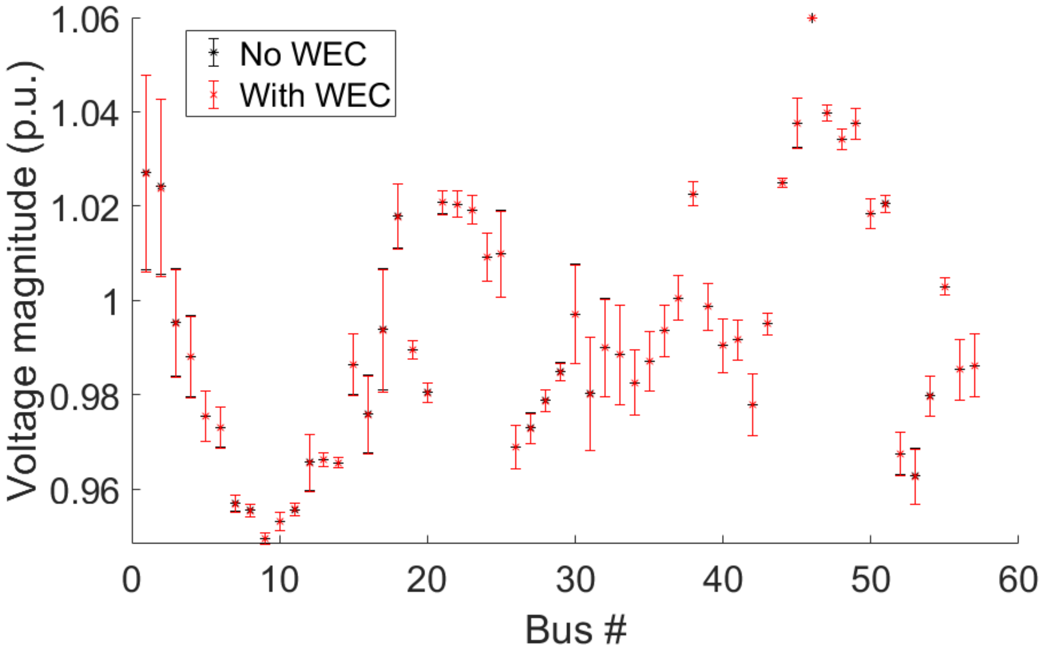
System performance with WECs added

- Power losses are slightly less with WECs
- Largest decreases when wind power is low and WECs give some compensation
- Very little difference in bus voltages

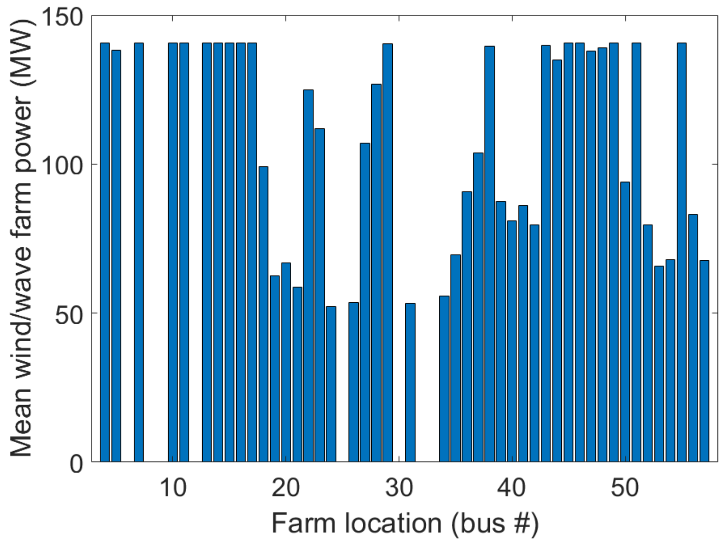


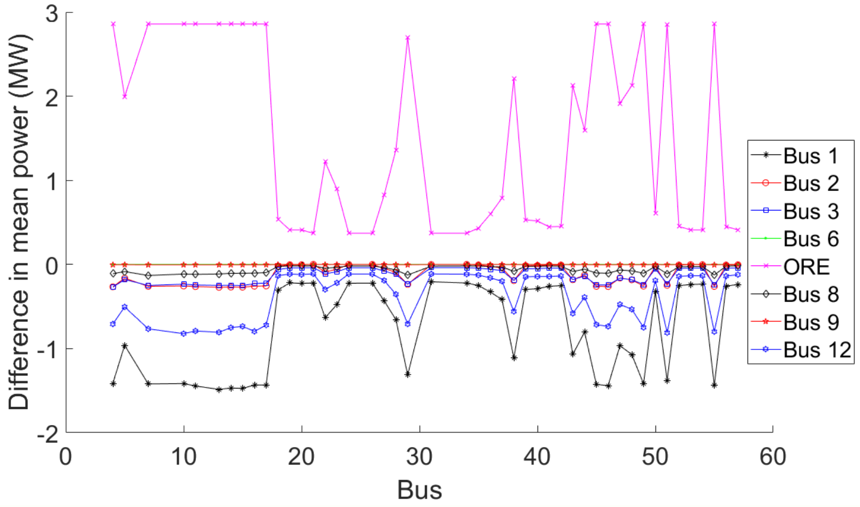


Bars are 1 standard deviation

Wind/wave farm placement is important

- **Not equal for all buses**
  Significant variation in performance depending on where the wind/wave farm is located
- Some placements utilize nearly 1/3 of the maximum possible such as 24 or 26
- Bus 13 is one that achieves the highest usage
- Bus 1 is the conventional generator most effected by the inclusion of WECs, regardless of the wind/wave farm placement





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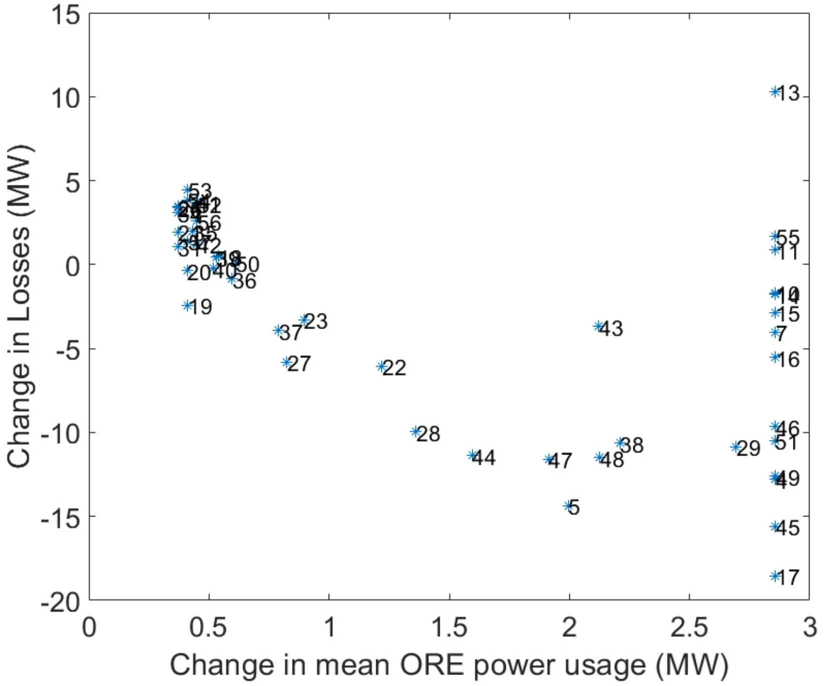
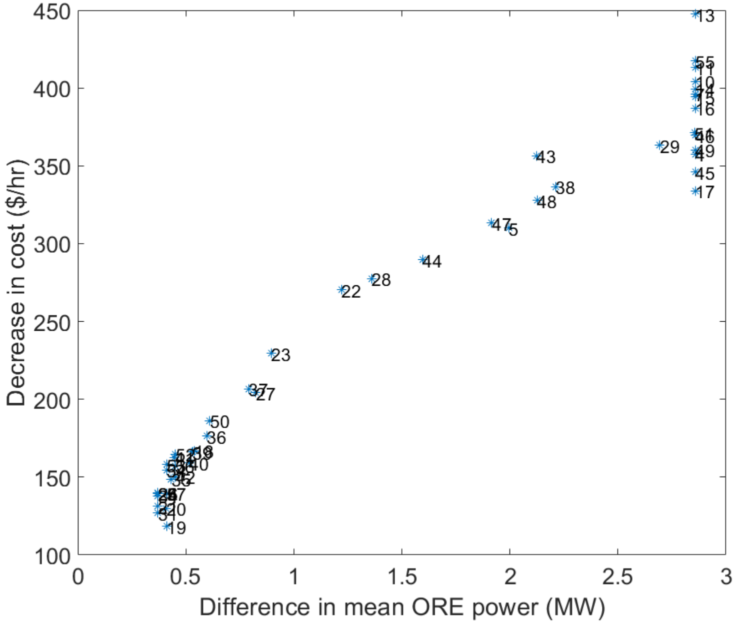
Losses and cost affected by placement

- A large decrease in losses can be found at both larger and lower ORE usage
- Even though buses 17 and 13 show similar ORE usage, 13 has 10 MW loss decrease, and bus 17 has an increase of almost 20 MW in loss
- The location can play a significant role in system performance





- As more wind/wave power is used, the cost decreases
- But, there is a large spread of cost changes at the maximum wind/wave power use
- Note that 13 has the best cost performance, while 17 has a worse performance
- This is due to the losses incurred

Conclusions

- East coast shallow waters led to relatively low additional energy for the wind/wave farm
  - An average of 1-2% more power
- Change in conventional power is similar
  - Nearly 1:1 in decrease in total conventional usage with additional power from WECs
  - For best performing bus
  - Conventional generator 1 is most effected by the addition of WECs
- Reactive power is effected less so, and is more complexly related to the addition of WECs
- Voltages are only slightly affected by the addition of WECs
- Location of wind/wave farm is key
  - Some buses could use as little as 1/3 of the additional available WEC power compared to others
- Even amongst buses which schedule the additional WEC power, losses and costs are not the same
  - Some buses whose scheduled power outputs are nearly identical still see different system performance
  - Due to location, bus 13 sees a decrease in system losses and a 30% decrease in cost when compared to bus 17.
  - Even amongst buses which schedule the additional WEC power, losses and costs are not the same
- ORE farm Location effects the amount of wind/wave power that can be utilized, but also the losses and cost of the system.

Acknowledgements

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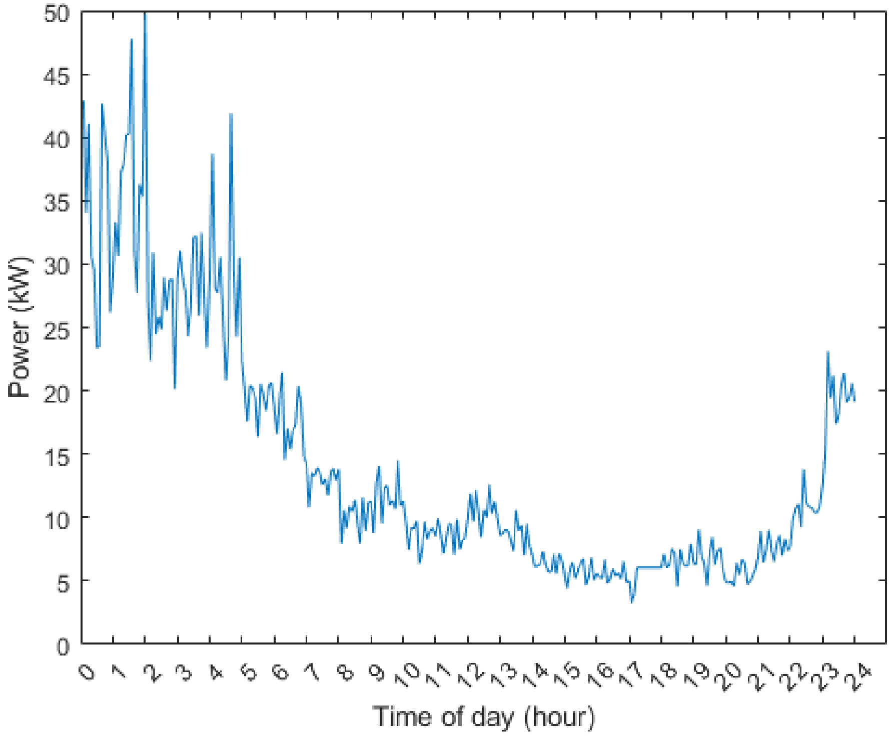
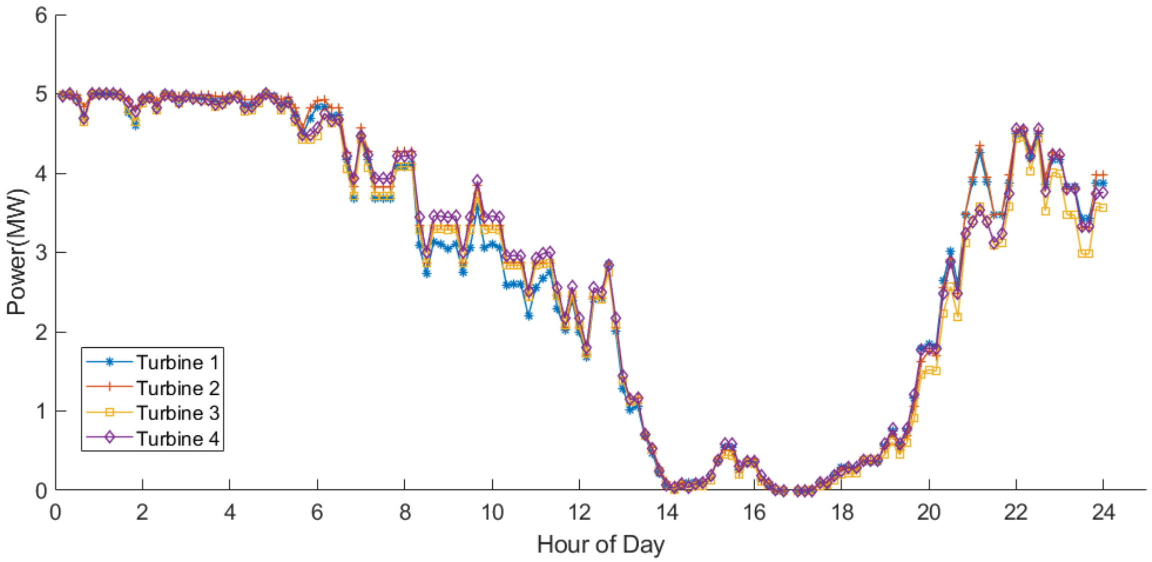
Supplemental plots





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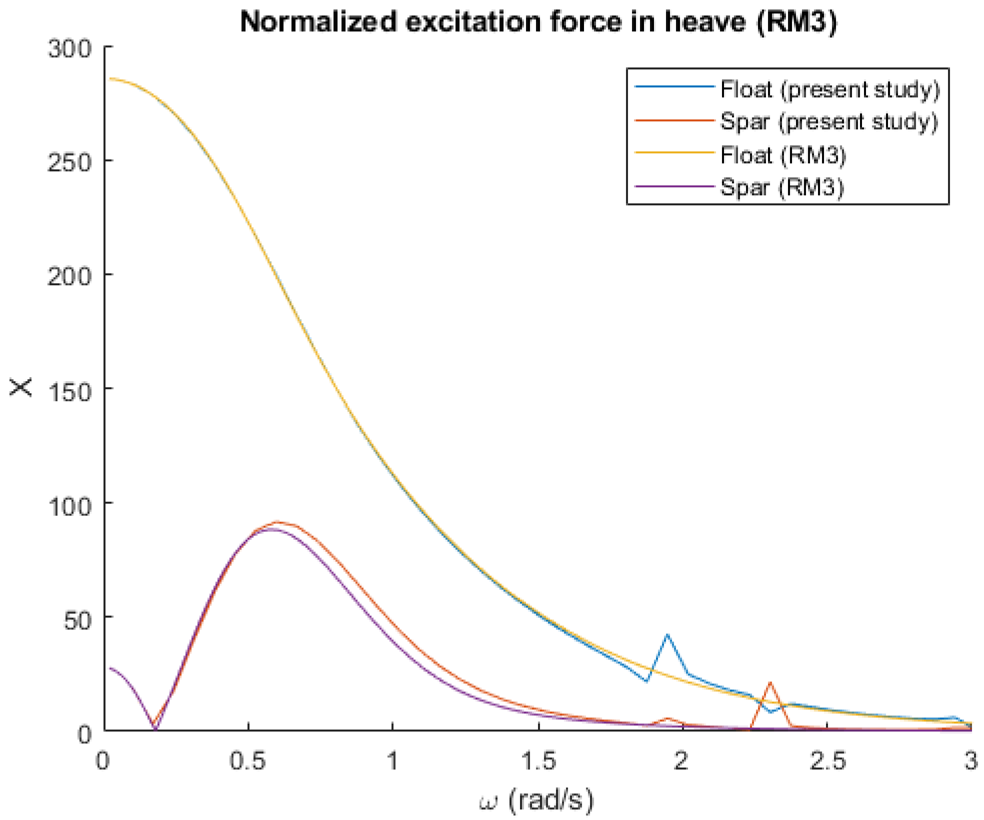

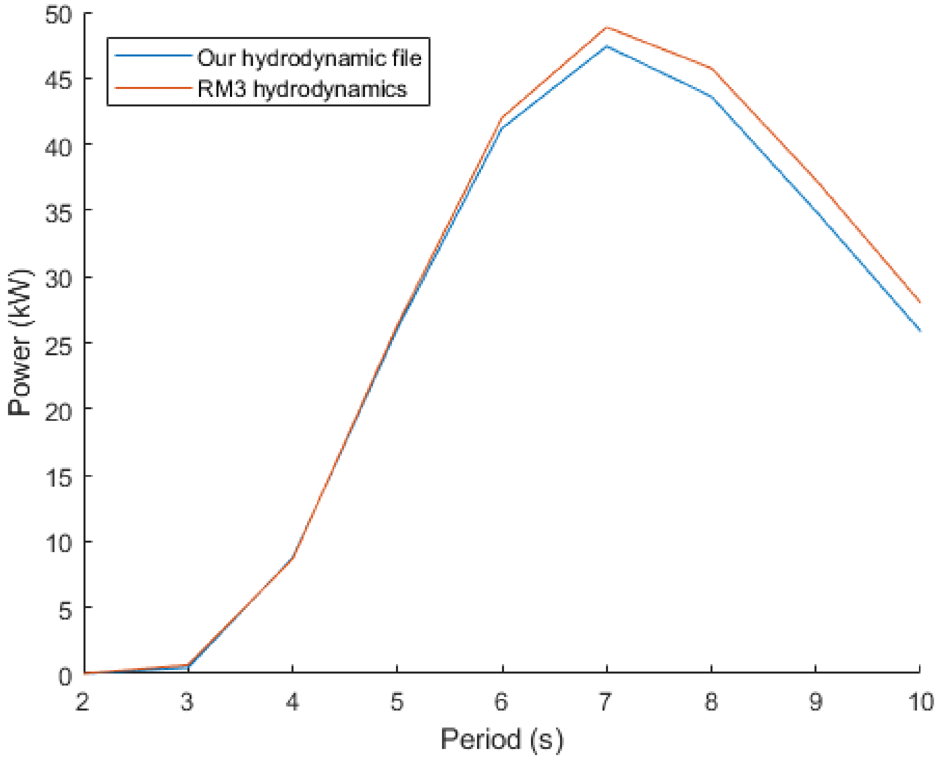

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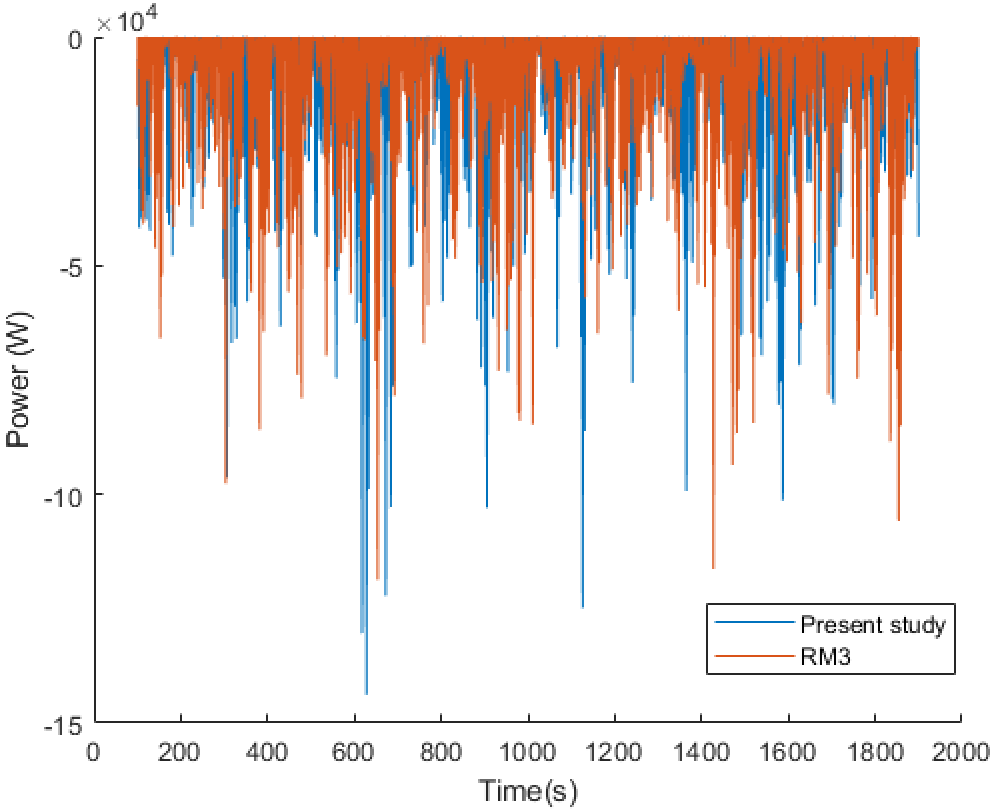
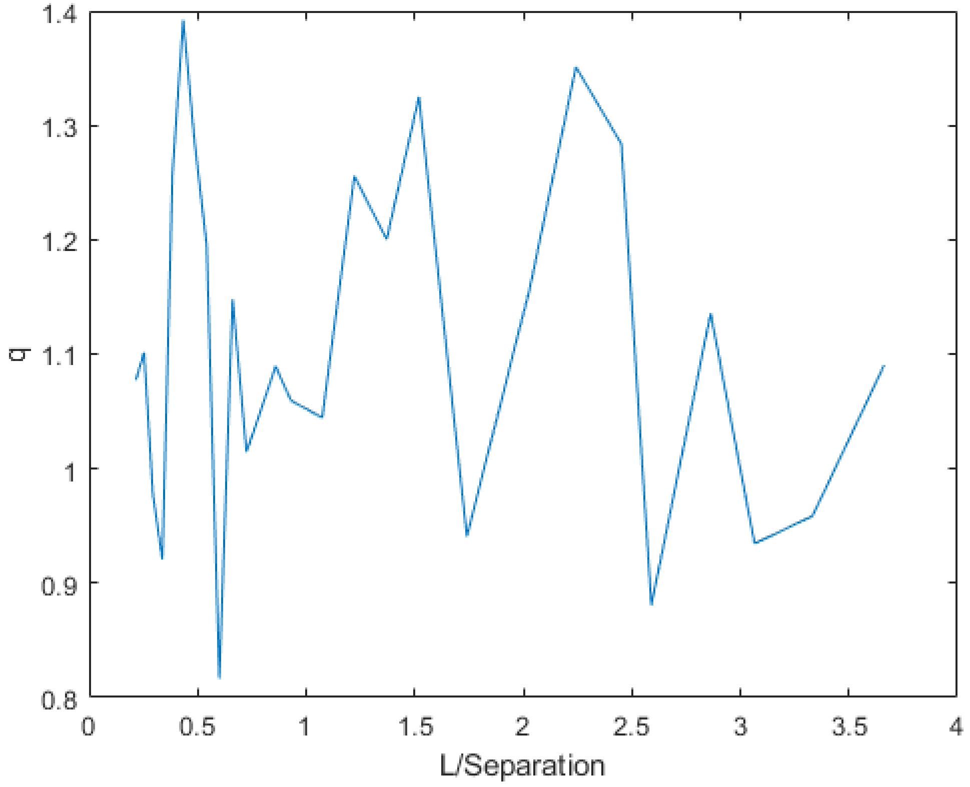
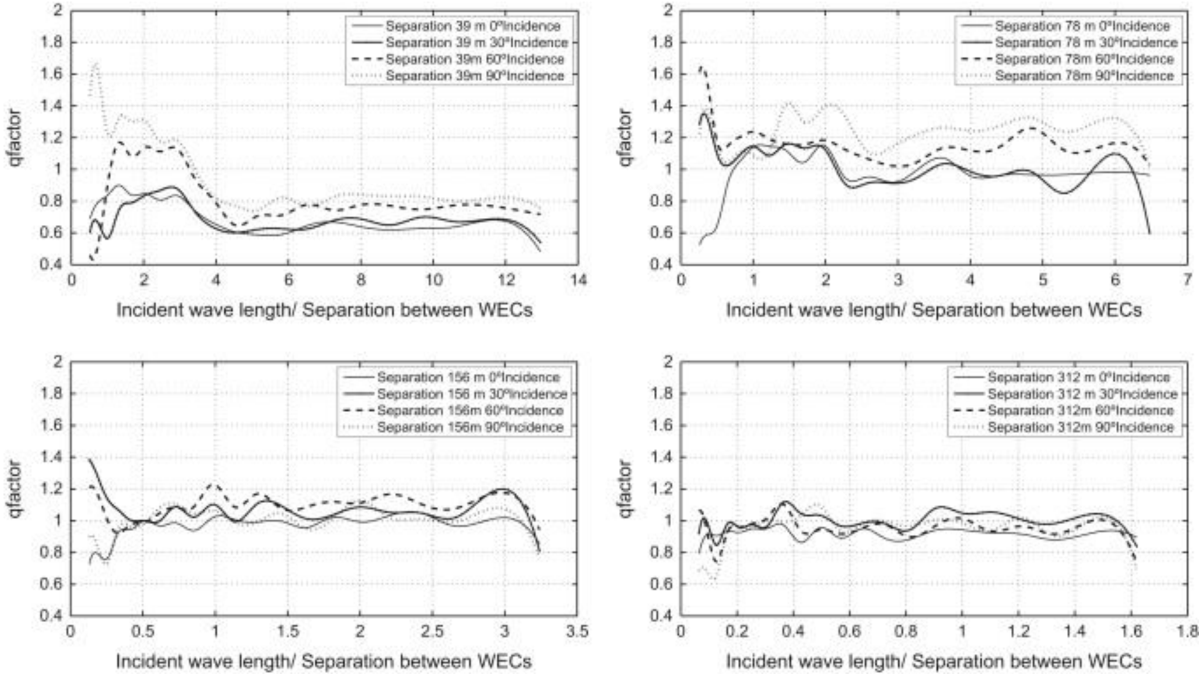


- Irregular wave with 10 s period
- Difference in mean power is 3.5%

Supplemental plots





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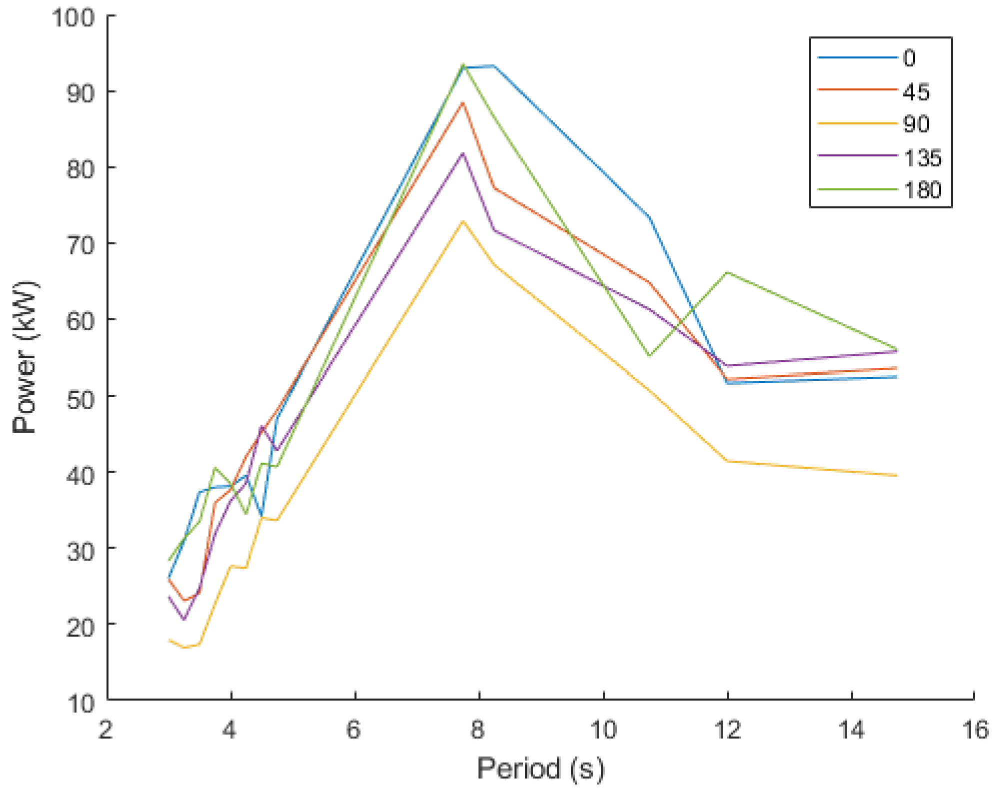

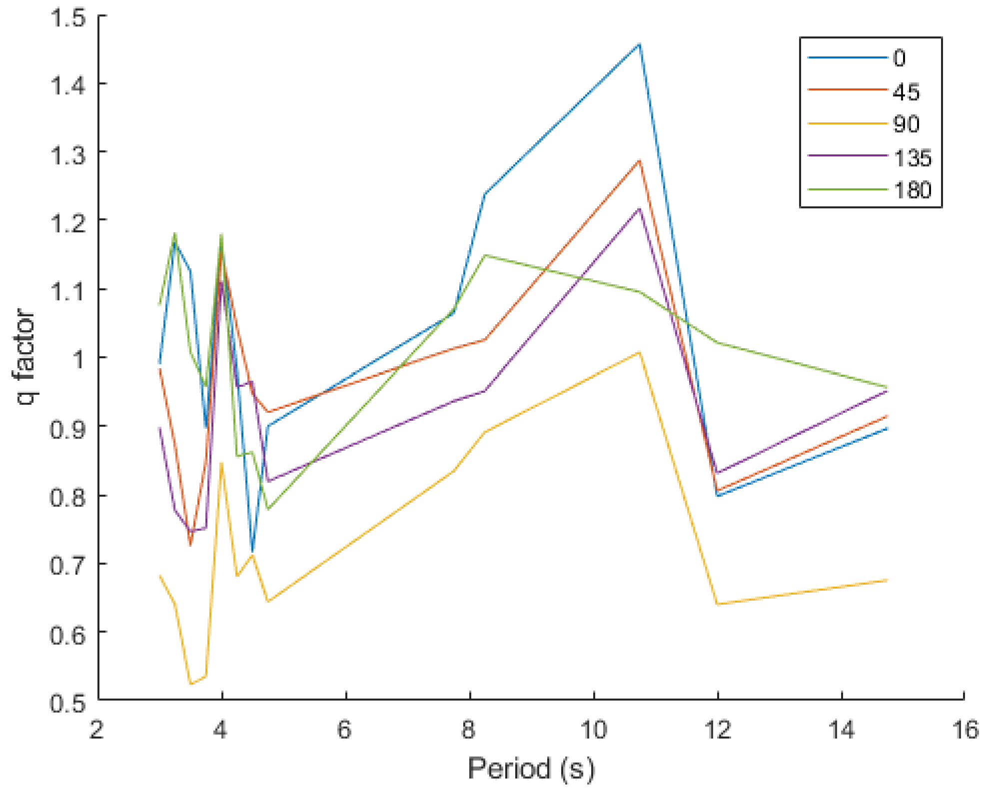

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