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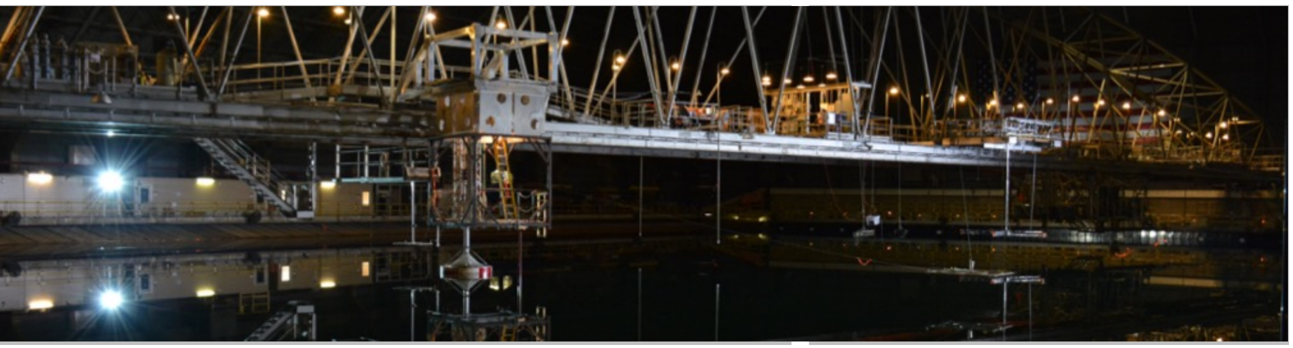

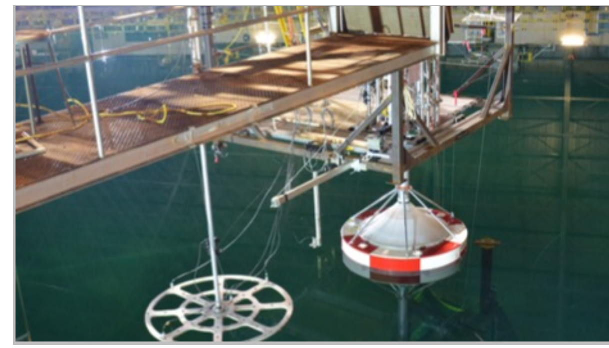

Wave Energy Conversion: Basic Principles and Implications for Design

Control Co-Design for Wind and Marine-hydro-kinetic Energy Systems
ARPA-E Workshop
July 26th, 2018

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Wave energy converters

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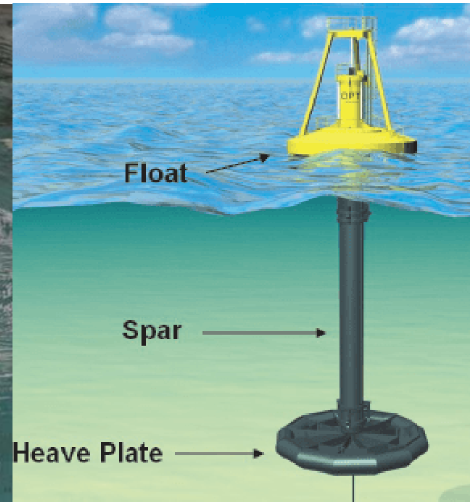
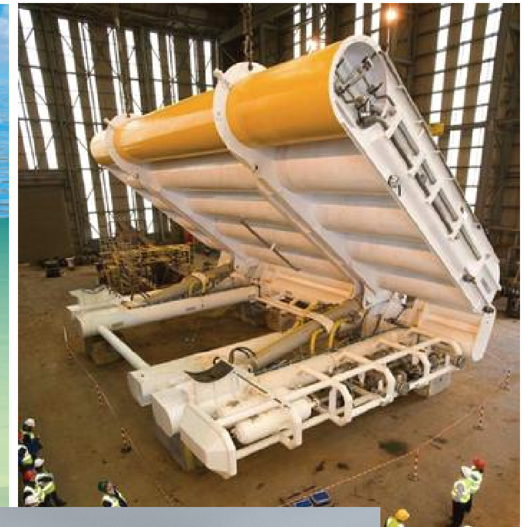
No standard configuration yet

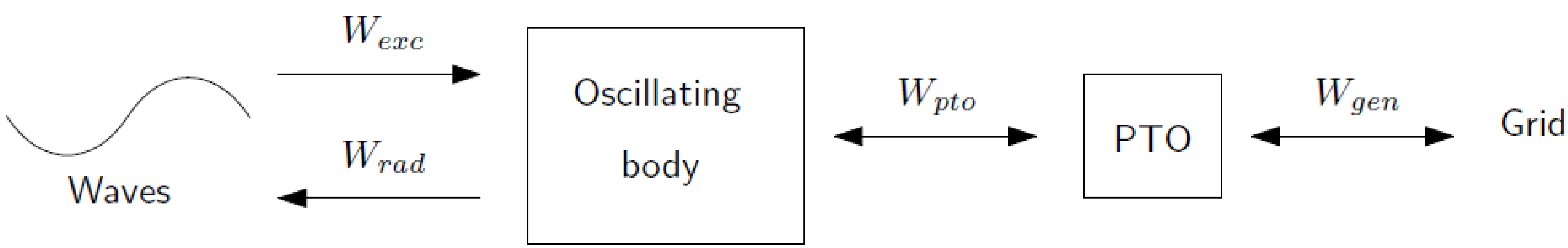


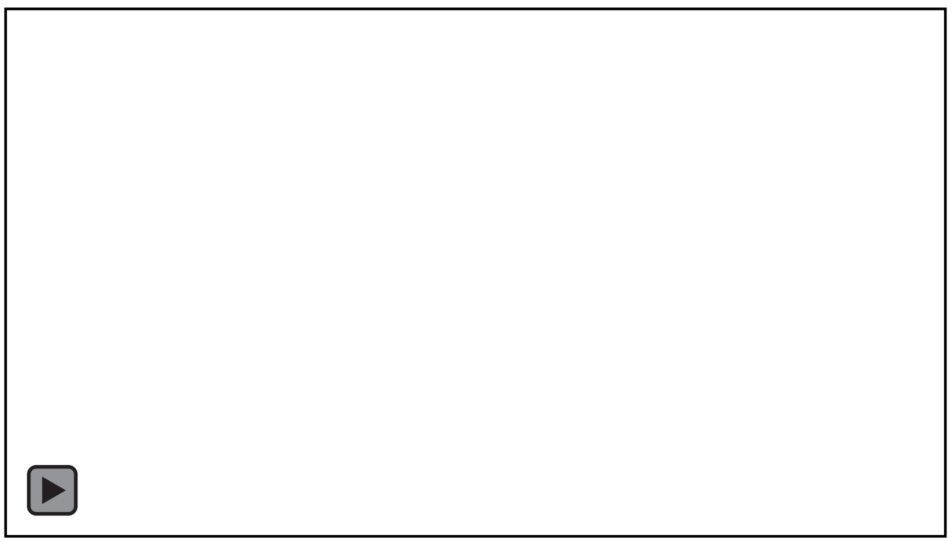


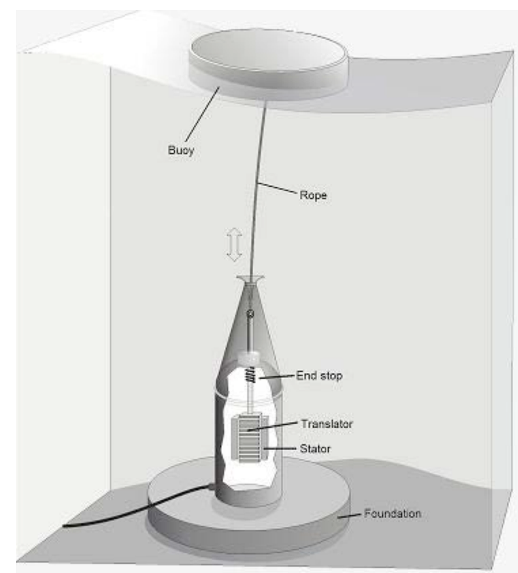
Wave spectra and bathymetry are very different around the world:
there will likely be multiple designs, depending on the location and end users

Power flow through a WEC

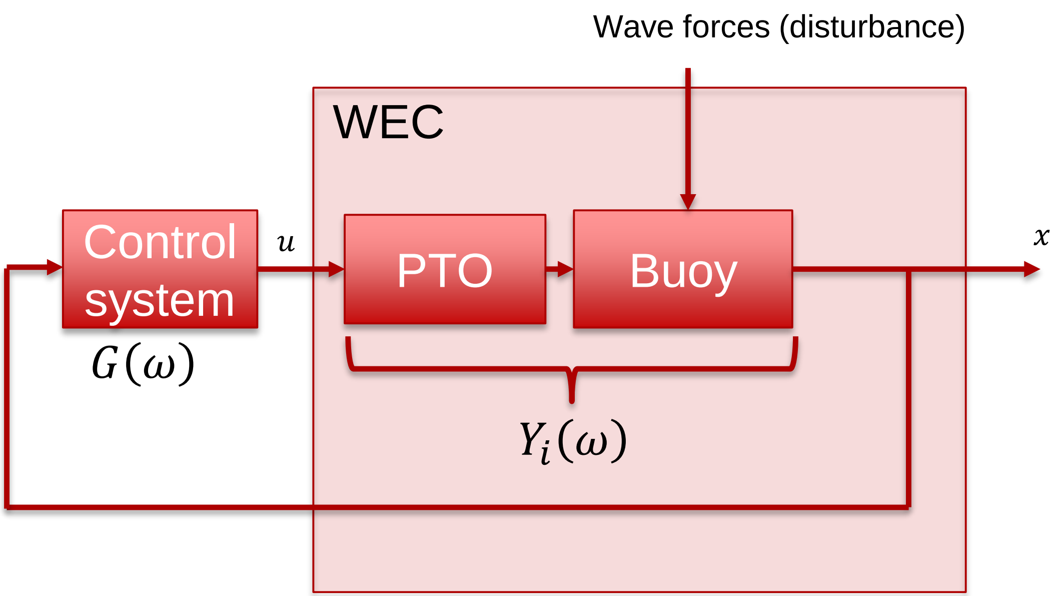
Energy transfer through an oscillating body wave energy converter



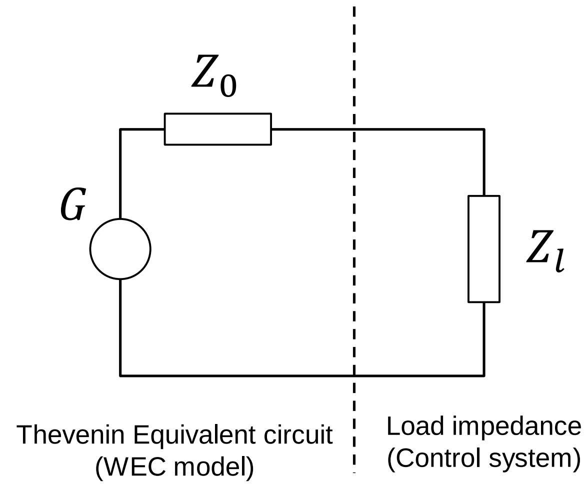




(Basic) Control problem of a WEC



Electrical circuit analogy



Optimal control problem ⟺ Impedance matching problem

$Z_l = Z_0^*$ ⟺ $G = -Z_i^*$

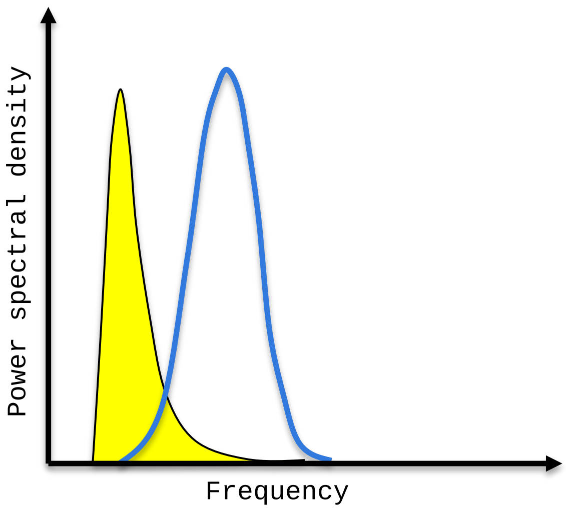
u = PTO input (e.g. generator's current, or buoy's force)

x = WEC state (e.g. generator's voltage, or buoy's velocity)

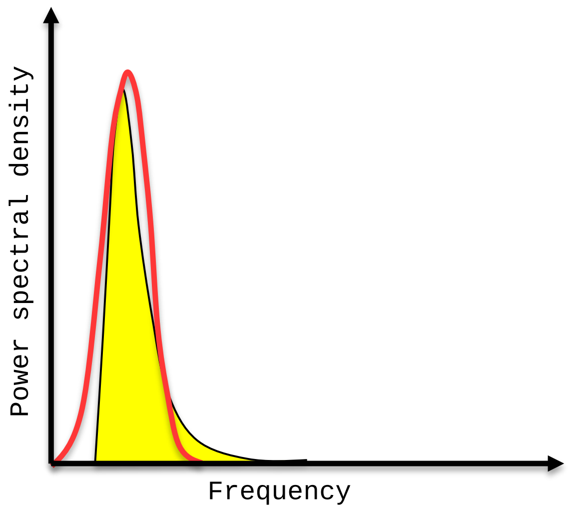
$^1/_{Y_i(\omega)} = {}^u/_y = Z_i(\omega)$ = intrinsic impedance of the device

Control problem of a WEC

Device non tuned



Device tuned



— Sea state spectral characteristics

— Device absorption characteristics – non tuned

— Device absorption characteristics – tuned

Considerations about power

Available wave power

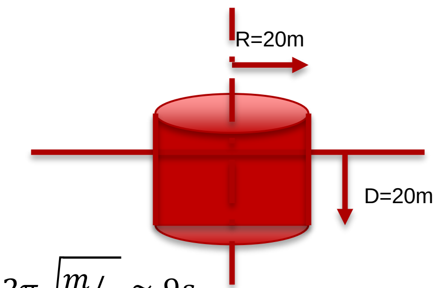
- $P \propto T$
- $P \propto H^2$
- Band limited $4 \le T \le 20$

Most of wave power is in a limited frequency range

Natural period increases with increasing size

Trying to design a naturally resonating could be VERY EXPENSIVE!

Example: Floating cylinder

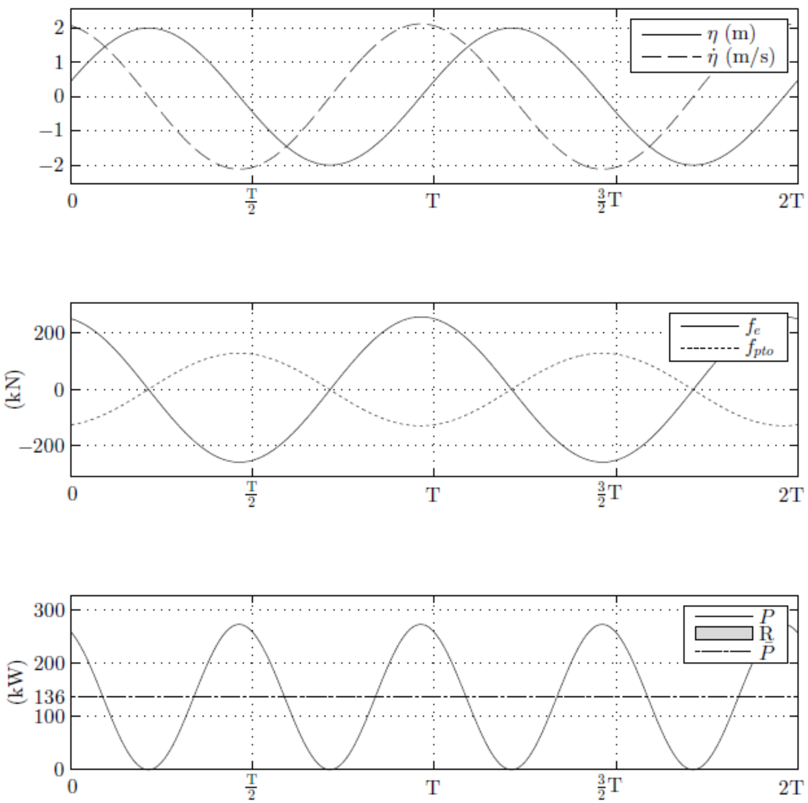


$$T_0 \approx 2\pi\sqrt{{}^{m}/_{k}} \approx 9s$$

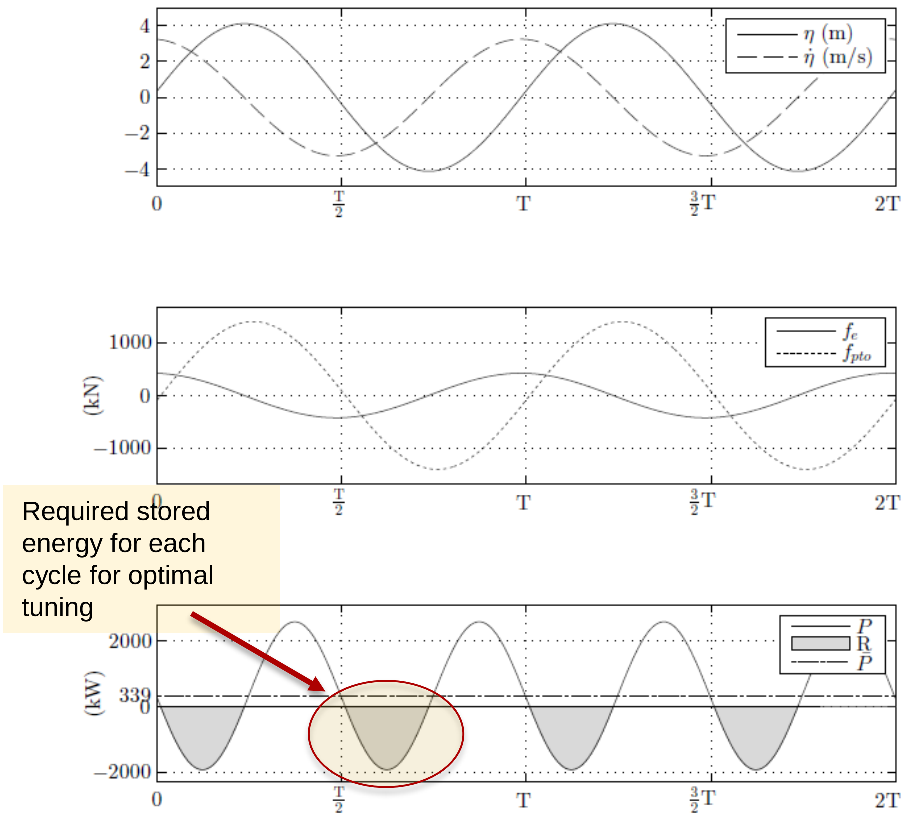
${}^1/_4$ the displacement of an aircraft carrier!! ($\approx 50000\ m^3$)

Energy storage and reactive power

Naturally tuned device



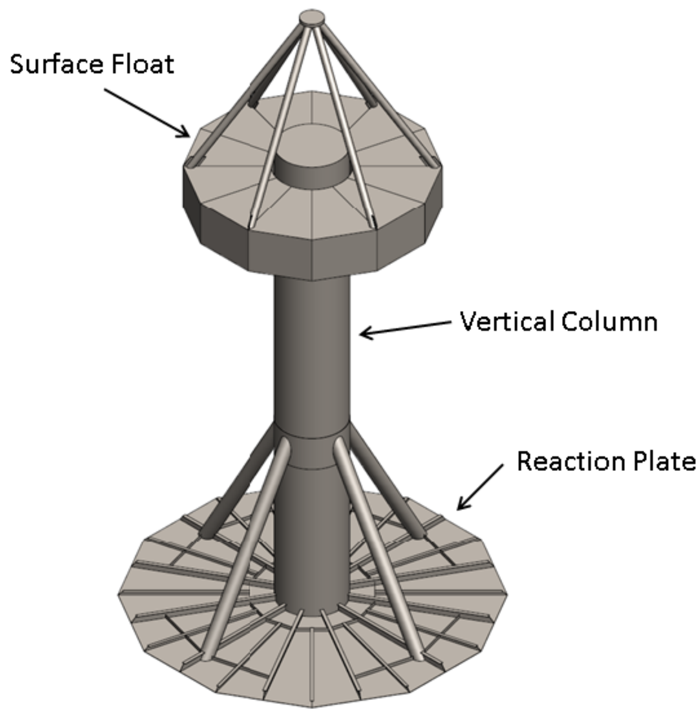
Device tuned using control and PTO design



Reference Model Project

LCOE ESTIMATION

Reference Model 3



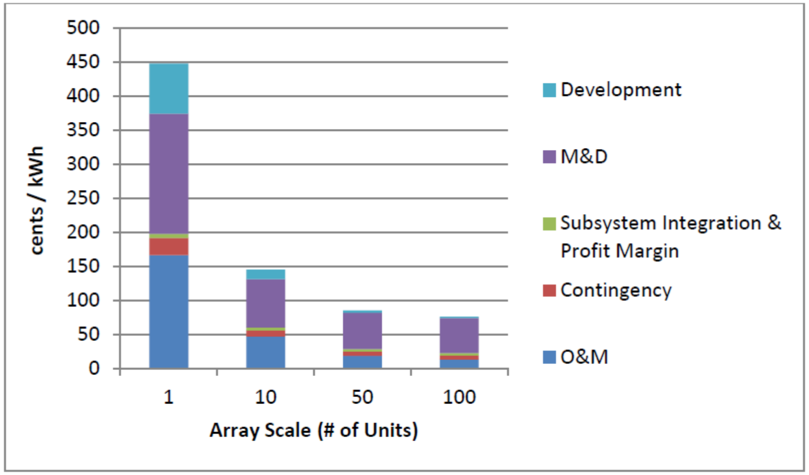


Figure 5-33. High-level LCOE (cents/kWh) breakdown per deployment scale for RM3.

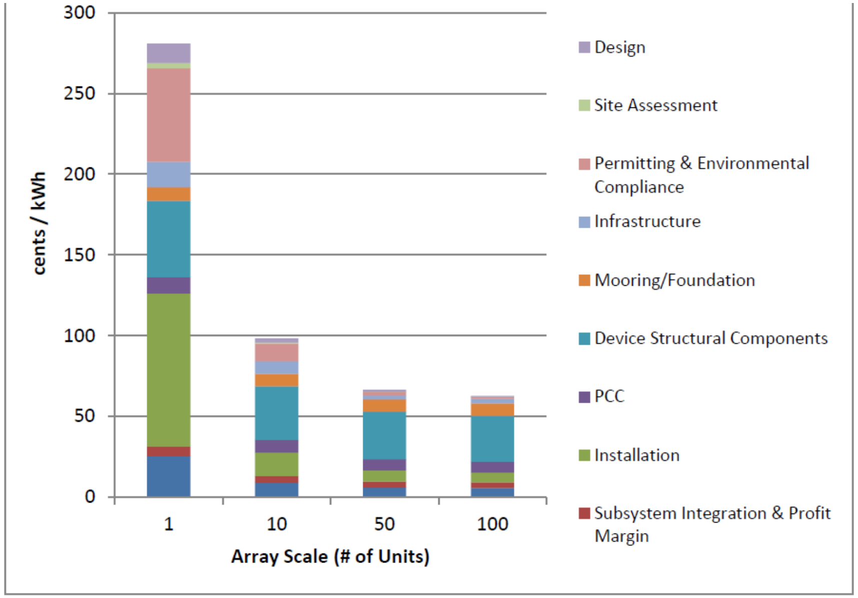
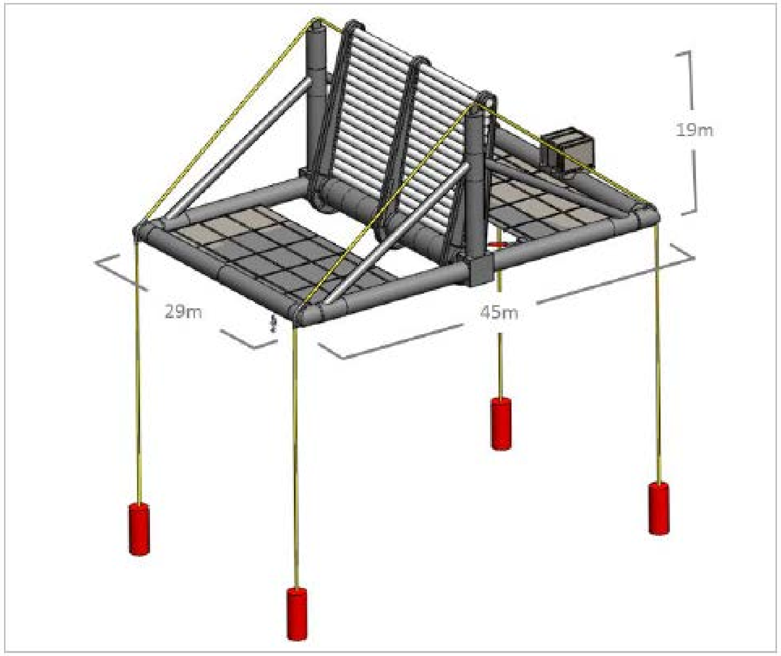


Figure 5-34. RM3 CapEx contributions to LCOE (cents/kWh) per deployment scale.

Reference Model 5



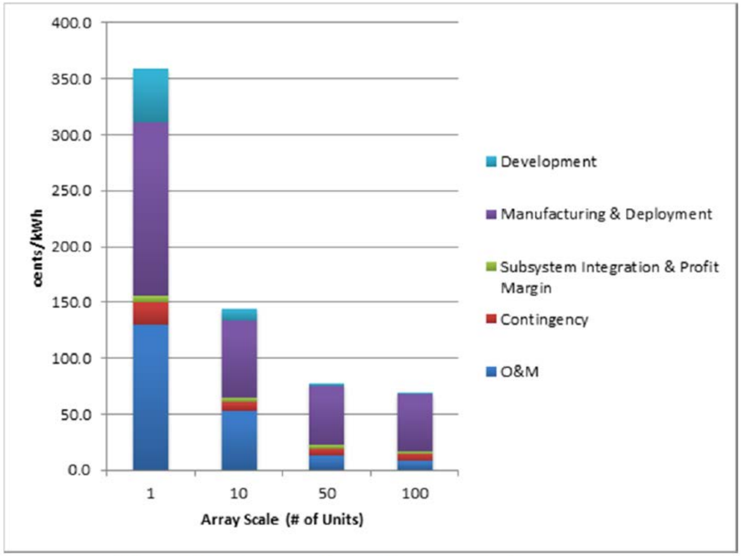


Figure 26. High-level LCOE (cents/kWh) breakdown per deployment scale for the RM5

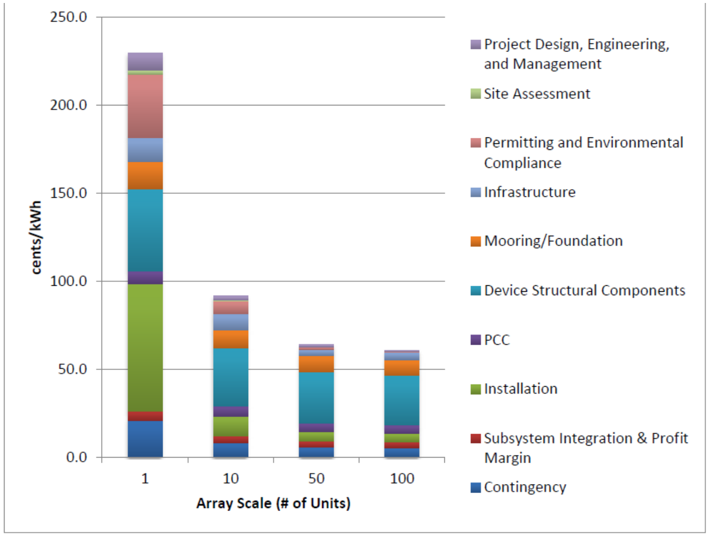
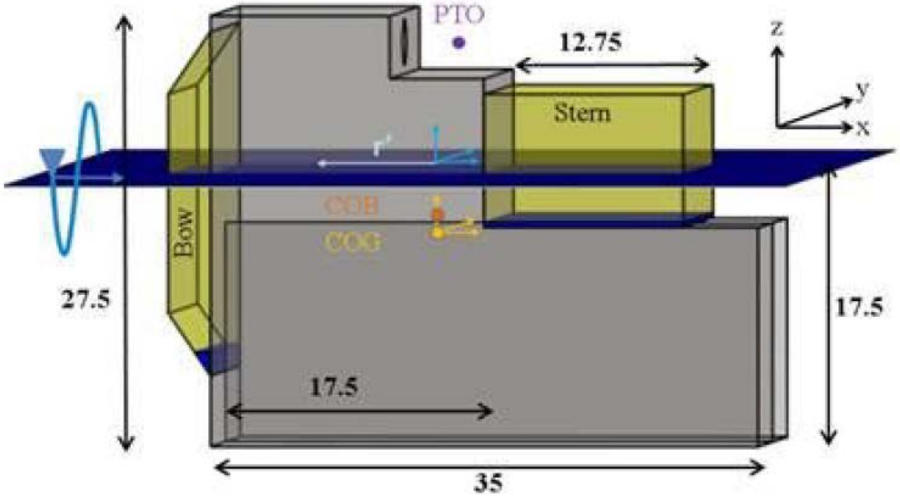
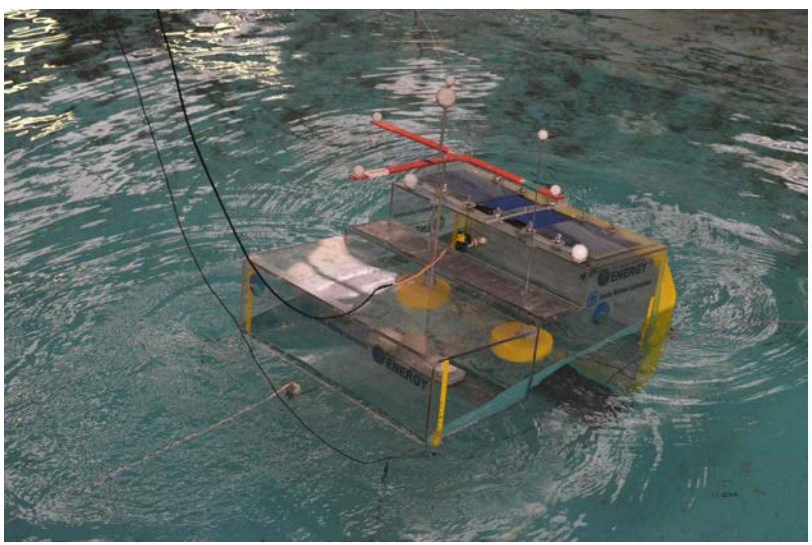


Figure 27. RM5 CapEx contributions to LCOE (cents/kWh) per deployment scale

Reference Model 6





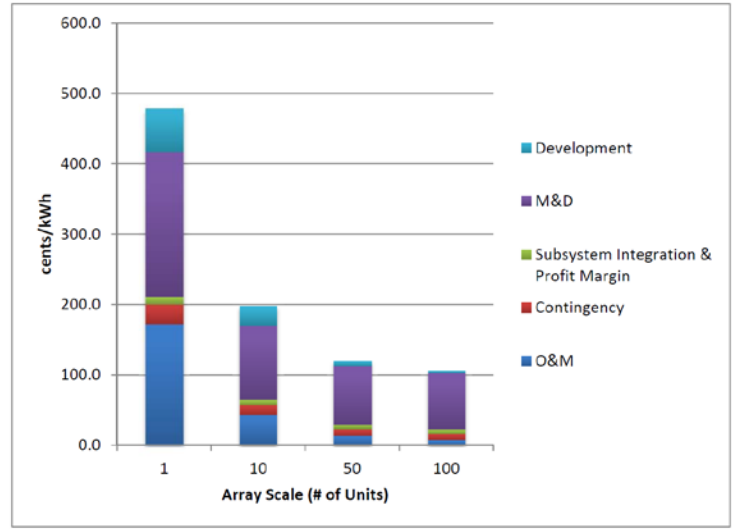


Figure 1-38: High-level LCOE (cents/kWh) breakdown per deployment scale for RM6.

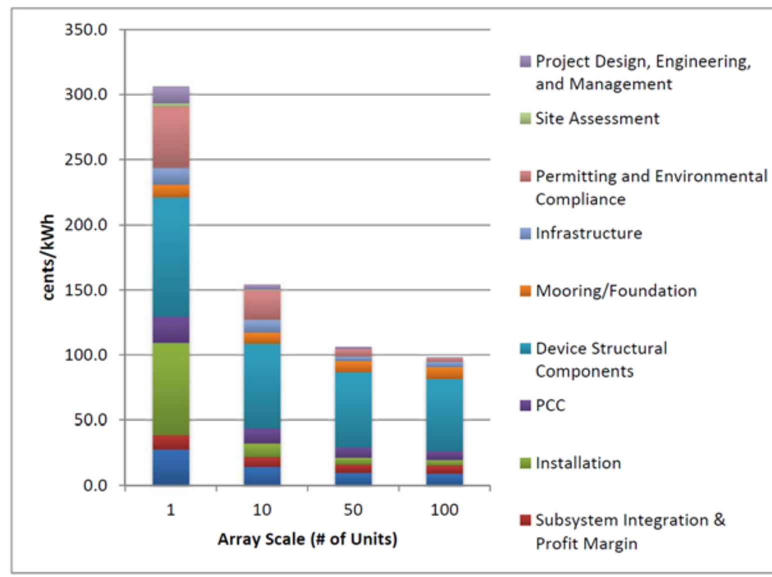
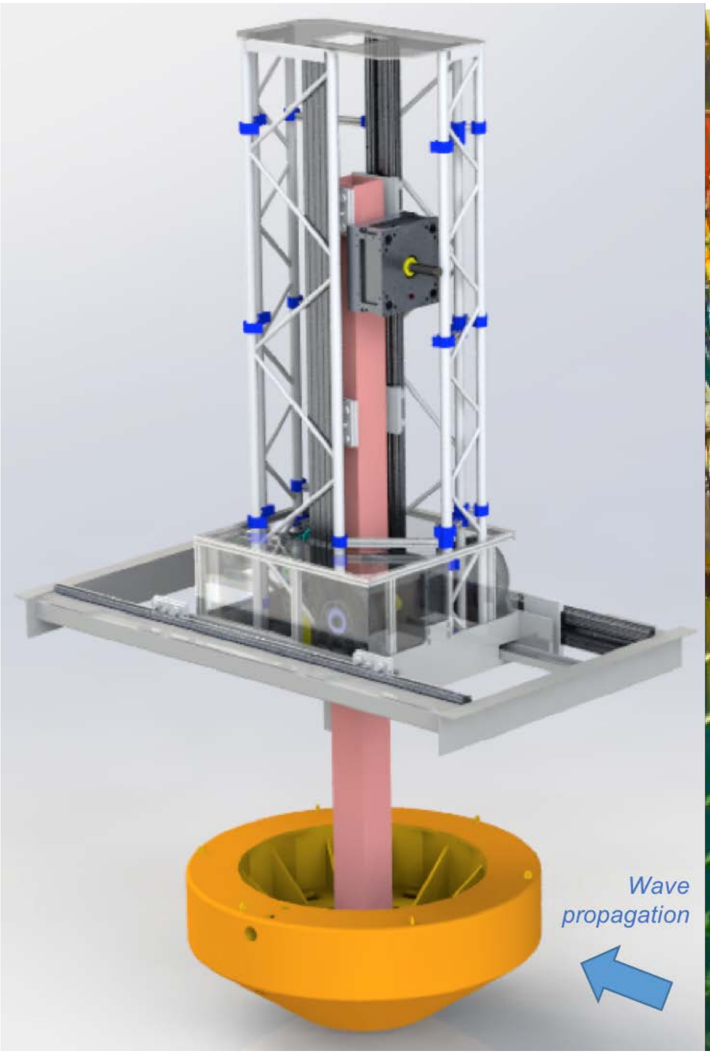


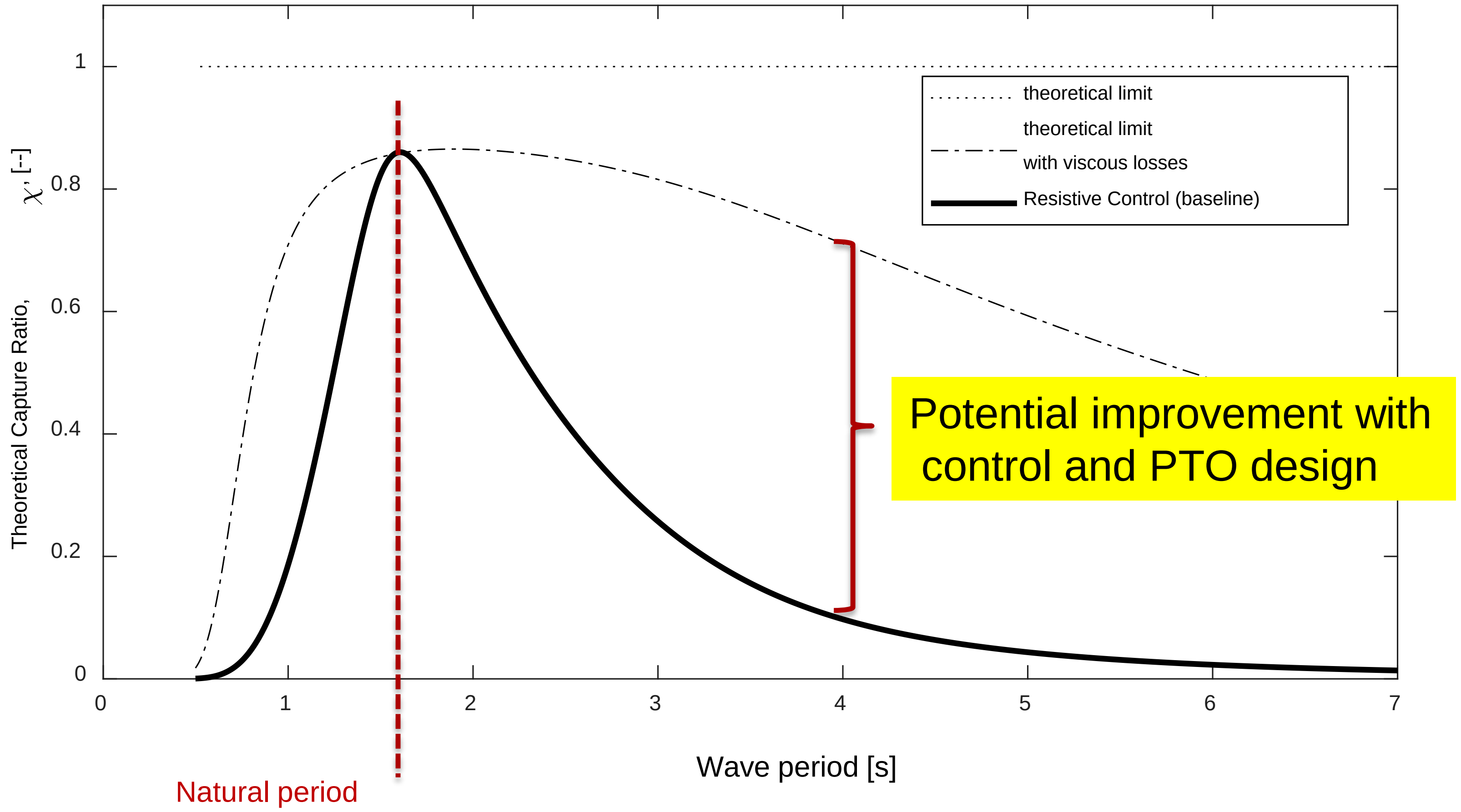
Figure 1-39: RM6 CapEx contributions to LCOE (cents/kWh) per deployment scale.

SANDIA ADVANCED WEC DYNAMICS AND CONTROL PROJECT

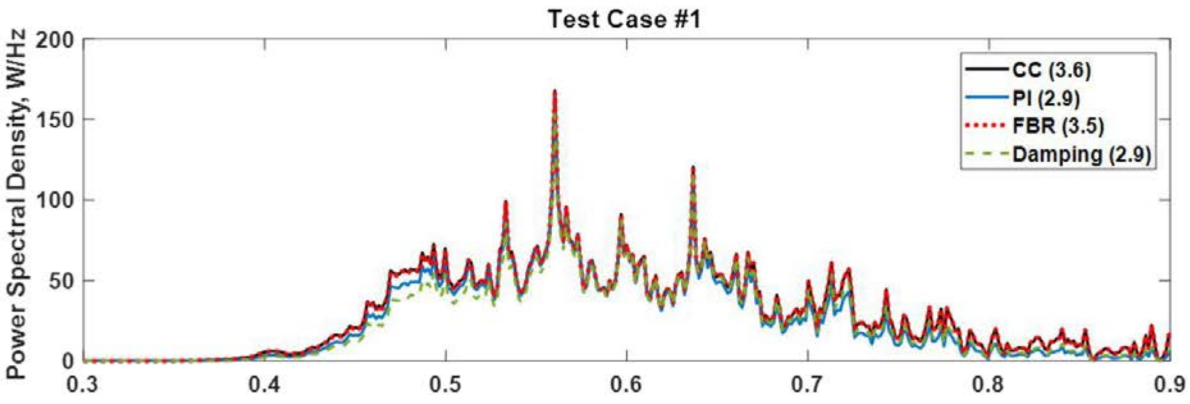
Device overview



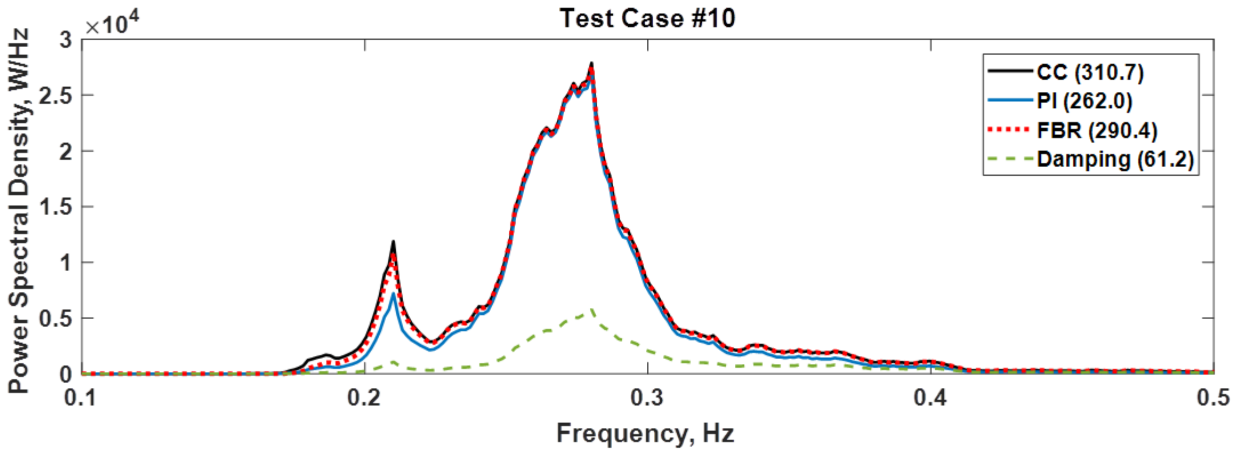
Control and PTO potential



Controllers performance



Naturally tuned WEC
(large device)



CC is the theoretical optimum (non causal)

Peak frequency of wave Spectrum smaller than WEC's natural frequency
(Small device in long waves)

Reducing device size

What happens to LCOE if we reduce device size and apply control co-design?

What we know

- Can improve absorbed power for small devices with advanced control and PTO
- Structural costs are dominant

Assumptions

- Device size = ½ original
- Same AEP
- Similar PTO costs
- Only considering effects on structural cost

Estimated 20% reduction in LCOE

Conclusions

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Control Co-Design

↓

Allows improvements in all the aspects of the design of a WEC

Good design of the system ≠ good design of individual subsystem