ASME
IDETC-CIE 2022

International Design Engineering Technical Conferences & Computers and Information in Engineering Conference

---

CONFERENCE: AUG. 14–17
EXHIBITION: AUG. 15–17
ST. LOUIS UNION STATION HOTEL,
ST. LOUIS, MISSOURI

MULTIDISCIPLINARY OPTIMIZATION TO REDUCE COST AND POWER VARIATION OF A WAVE ENERGY CONVERTER

IDETC2022-90227

Rebecca McCabe, Olivia Murphy, Maha Haji
Symbiotic Engineering Analysis Lab
Cornell University

ASME
IDETC-CIE 2022
International Design Engineering Technical Conferences
& Computers and Information in Engineering Conference

Motivation

Goal: use **MDO** to minimize energy cost and power variation of the **RM3 WEC**

MDO	WEC	RM3
Multidisciplinary · **D**esign · **O**ptimization	**W**ave · **E**nergy · **C**onverter	**R**eference · **M**odel · **3**
• Procedure to optimize engineering systems with cross-discipline coupling	• Renewable energy for utility grids and distributed offshore projects • Costs more than solar and wind, but perhaps more consistent power	• Reference WEC design by NREL and Sandia [10] • Comprised of two-body floating point absorber

Problem Formulation

Parameter(s)

ObjectiveFunction (s) → $\text{minimize } J(x, p)$

Inequality Constraint(s) → $\text{subject to } g(x, p) < 0$

Equality Constraint(s) → $h(x, p) = 0$

$$x_{i,LB} \leq x_i \leq x_{i,UB}$$

Lower Bound

Design Variable(s)

Upper Bound

Problem Formulation: J

Objective 1: LCOE	Objective 2: c_v
Levelized · **C**ost · **o**f · **E**nergy	Power **C**oefficient of **V**ariation
• \$/kWh • Electricity price over full system lifetime	• σ/μ • Normalized standard deviation of power across sea states

$$\begin{aligned} &\text{minimize } \boxed{\mathbf{J}(\mathbf{x}, \mathbf{p})} \\ &\text{subject to } \mathbf{g}(\mathbf{x}, \mathbf{p}) < 0 \\ &\qquad\qquad \mathbf{h}(\mathbf{x}, \mathbf{p}) = 0 \\ &x_{i,LB} \leq x_i \leq x_{i,UB} \end{aligned}$$

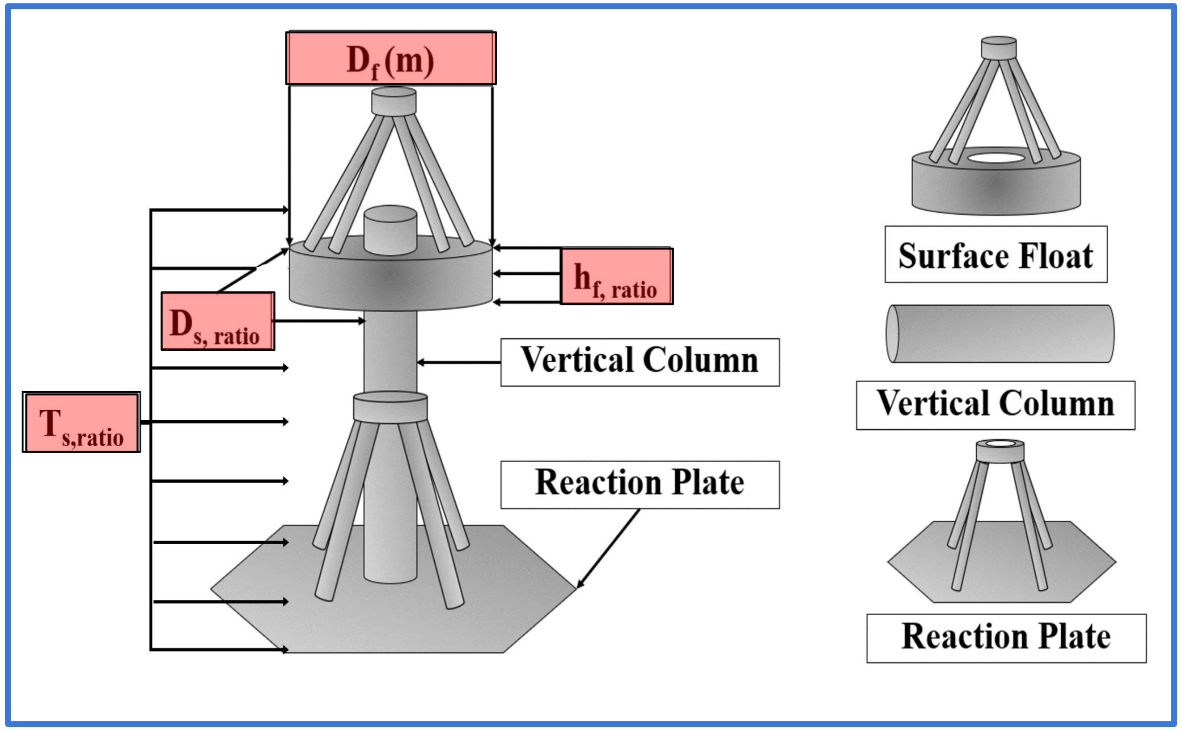
Problem Formulation: x

$$\begin{aligned} \text{minimize} \quad & J(\boxed{x}, p) \\ \text{subject to} \quad & g(\boxed{x}, p) < 0 \\ & h(\boxed{x}, p) = 0 \\ & x_{i,LB} \le x_i \le x_{i,UB} \end{aligned}$$

7 Design Variables

	Design Variable	Description
Geometry	D_f	WEC Surface Float Outer Diameter
Geometry	$D_{s,ratio}$	Ratio of WEC Surface Float Inner Diameter to Outer Diameter
Geometry	$h_{f,ratio}$	Ratio of WEC Surface Float Height to Outer Diameter
Geometry	$T_{s,ratio}$	Percent of WEC Spar Submergence
WEC Control	F_{max}	Maximum Powertrain Force
WEC Control	B_p	Powertrain/Controller Damping
WEC Control	ω_n	Controller Natural Frequency

WEC Visuals



Inspired by, SANDIA REPORT, SAND2014-9040, Vincent S. Neary, Mirko Previsic, et al.

Source: Crozier, Richard. "RM3 Point Absorber." *YouTube*, YouTube, 13 June 2018, https://www.youtube.com/watch?v=KNbzy6iamM0.

Problem Formulation: p

$$\text{minimize } \mathbf{J}(\mathbf{x}, \boxed{\mathbf{p}})$$
$$\text{subject to } \mathbf{g}(\mathbf{x}, \boxed{\mathbf{p}}) < 0$$
$$\mathbf{h}(\mathbf{x}, \boxed{\mathbf{p}}) = 0$$
$$x_{i,LB} \leq x_i \leq x_{i,UB}$$

33 Parameters

	Parameter	Description
Dynamics	H_s	Wave Height
	T	Wave Period
	pto_{eff}	Power Take-Off Efficiency
Economics	$cost_m$	Material Cost
	FCR	Fixed Charge Rate
	N_{WEC}	# of WECs in Array
Structures	σ_y	Material Yield Strength
	E	Material Young's Modulus
	ρ_m	Material Density
Geometry	D_d/D_s	Normalized Damping Plate Diameter
	T_s/D_s	Normalized Spar Draft
	T_f/h_f	Normalized Float Draft
	+ 21 Additional Parameters	

Problem Formulation: g

minimize $J(x, p)$
subject to $\boxed{g(x, p) < 0}$
$\cancel{h(x, p) = 0}$

$x_{i,LB} \leq x_i \leq x_{i,UB}$

14 Inequality Constraints

	Constr.	Description	<	>	Units
Dynamics	$h_{s,extra}$	Prevent Float Above Top of the Spar	-	0	m
Dynamics	$F_{p,max}/F_{max}$	Prevent Irrelevant Max Force	-	1	-
Dynamics	μ	Net Generated Power	-	0	kW
Economics	LCOE	Prevent LCOE Greater Than Nominal	$LCOE_{max}$	-	$/kWh
Structures	FOS (4)	Structural Factor of Safety	-	FOS_{min}	-
Geometry	V_{fpct}	Prevent Float too Heavy/Light	1	0	-
Geometry	V_{spct}	Prevent Spar to Heavy/Light	1	0	-
Geometry	GM	Metacentric Height	-	0	m
Geometry	D_d	Minimum Damping Plate Diameter	-	$D_{d,min}$	m

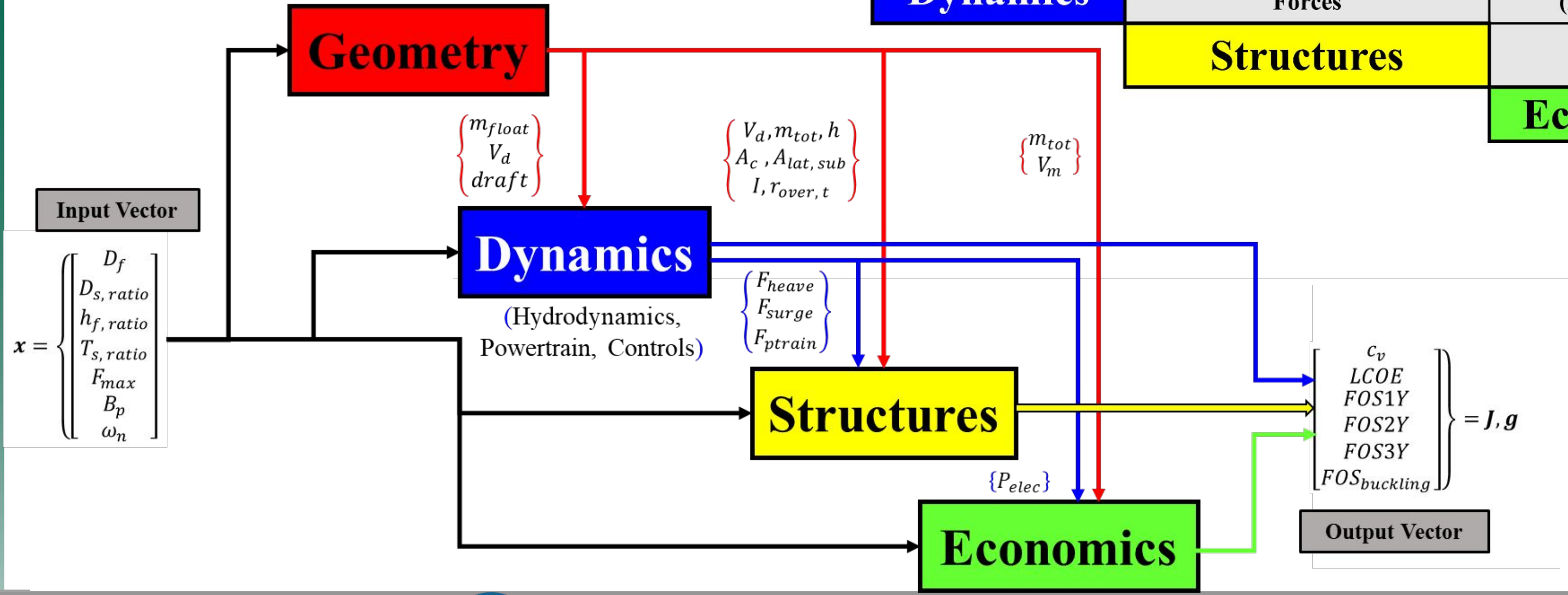
4 structural Factors of Safety (FOS)

1. Float yield
2. Reaction plate yield
3. Column yield
4. Column buckling

Simulation Structure: Four Modules

Input: (x, p)	x: $D_{s,ratio}$, D_f, $h_{f,ratio}$ p: t_{ft}, t_{fr}, t_{fc}, t_{fb}, t_{sr}, ρ_m, D_d/D_s, T_s/D_s, h_d/D_s, T_f/h_f	x: D_f, ω_n, F_{max}, B_p p: T, Hs, JPD, T_{struct}, Hs_{struct}, ρ_w, g	x: $T_{s,ratio}$ p: ρ_w, g, σ_y, E, t_r, B_{min}, FOS_{min}, $D_{d,min}$	p: $cost_m$, FCR, N_{WEC}, $LCOE_{max}$	
	Geometry	Surface float mass, WEC displaced volume, Submerged float geometry	WEC displaced volume, WEC mass, Vertical column length, WEC cross-sectional area, WEC submerged lateral area, WEC second moment of inertia, Float height	WEC mass, WEC material volume	
		Dynamics	Heave, Surge, and Powertrain Forces	Generated Power (Electricity)	Power Variation, c_v
			Structures		Yield FOS, Buckling FOS, B, GM
				Economics	LCOE
					Output: J(x, p), g(x, p)

Block Diagram:



N² Diagram:
★ No Loops
Runtime: 0.2 ms

Dynamics Modeling Assumptions

	This Model	
Overall simulation	**Frequency** domain simulation with linear hydrodynamics, powertrain, and controls	
Hydrodynamic coefficients	**Analytical** approximations with tuning	
Saturation strategy	Peak powertrain **force** (describing function)	
Controller tuning	**Same** damping and stiffness for all sea states	
Maximum storm loadcase	Float **moves** on spar (analytical)	

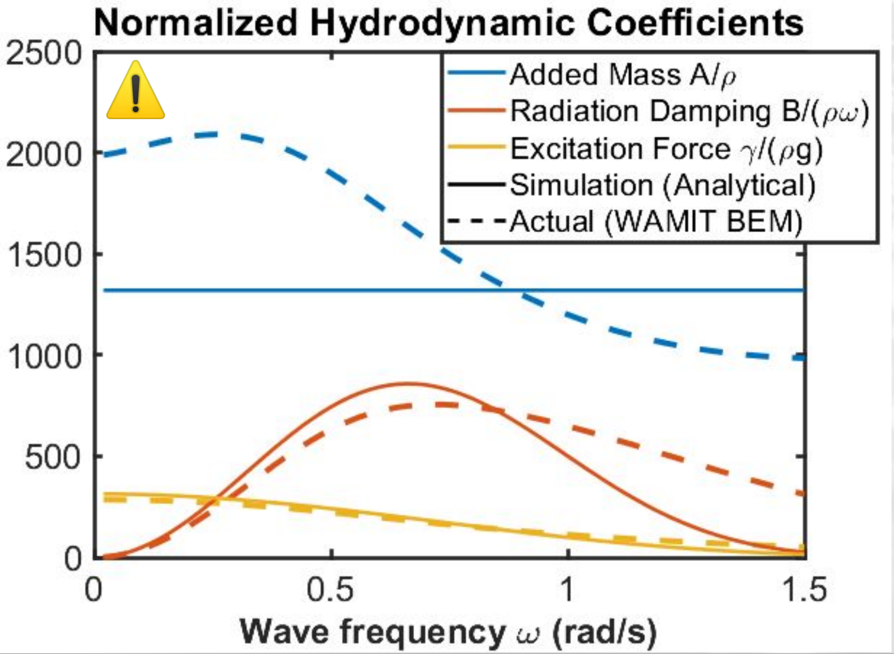
Model Validation against Nominal RM3

Mass Validation		
	Simulated	Actual
Surface Float	196 MT	208 MT
Vertical Column	210 MT	224 MT
Reaction Plate	267 MT	245 MT
Total	673 MT	680 MT

Cost Validation (100 WECs)		
	Simulated	Actual
CapEX	$ 416 M	$ 390 M
OpEX * ⚠	$ 15 M	$ 9 M
Total	$ 431 M	$ 399 M

* Discrepancy: cost scales nonlinearly with number of devices

Performance Validation		
	Simulated	Actual
Average Power	86.2 kW	85.9 kW
Max Structural Force	8460 kN	8500 kN
LCOE	$0.87 / kWh	$0.76 / kWh
c_v	75.5%	71.1%



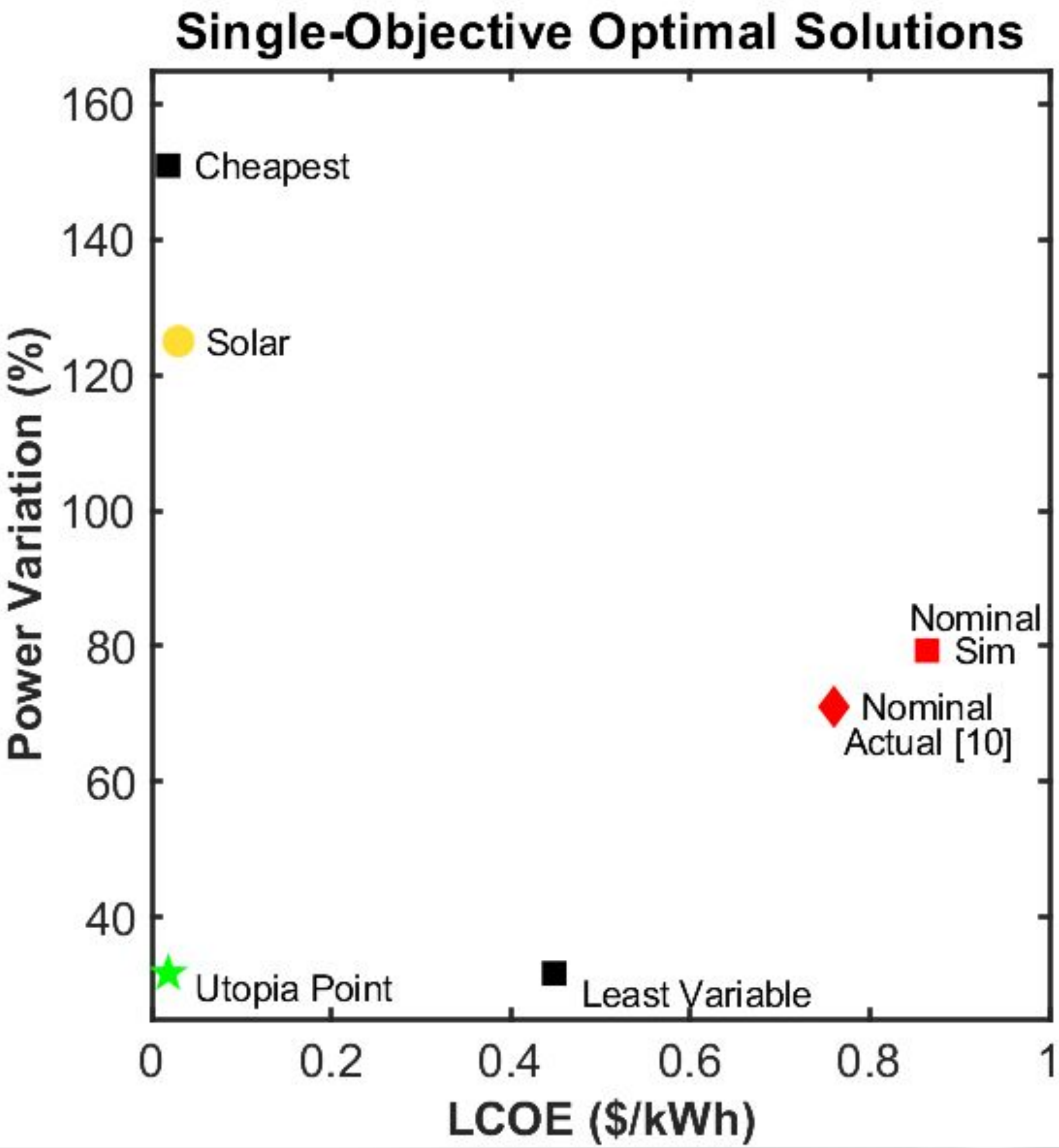
ASME IDETC-CIE 2022
International Design Engineering Technical Conferences & Computers and Information in Engineering Conference

Single Objective Optimization

Gradient Based Algorithm:

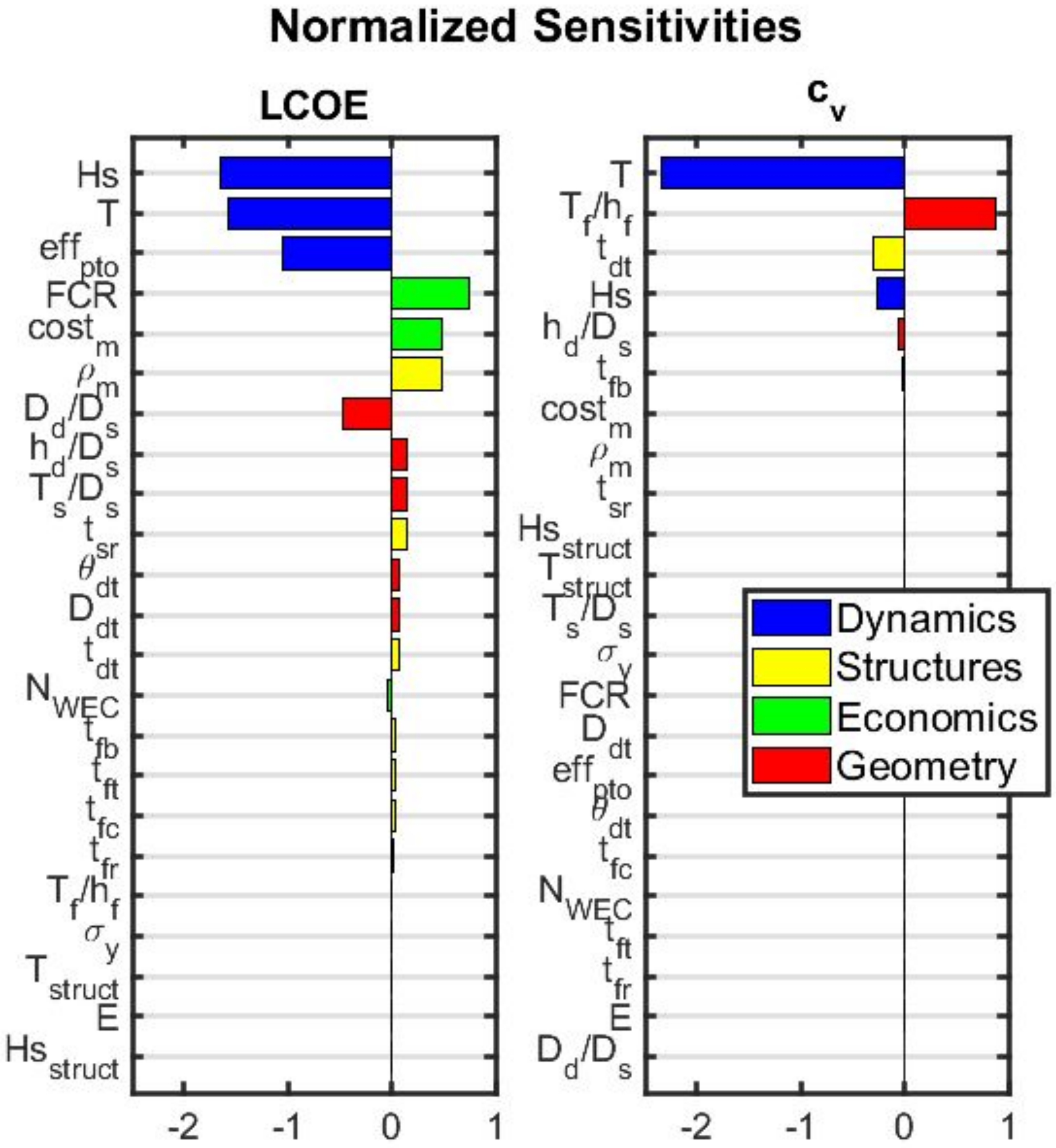
Sequential Quadratic Programming (SQP)

	Nom [10]	Min LCOE	Min c_v	Solar
LCOE ($/kWh)	0.76	**0.02**	0.48	0.03
c_v (%)	71	153	**35**	125



Parameter Sensitivities

- Normalized: 1 means 10% increase in parameter causes 10% increase in objective
- **LCOE** sensitive to **dynamic** and **economic** parameters, insensitive to **structural** and **geometric** parameters
- **c_v** insensitive overall, except to wave period and float submersion
- Implies correct choice of design variables



ASME IDETC-CIE 2022
International Design Engineering Technical Conferences & Computers and Information in Engineering Conference

Sensitivity to Deployment Location

Optimal Design Variable Values for $LCOE_{min}$									
Location		D_f	$D_{s,ratio}$	$h_{f,ratio}$	$T_{s,ratio}$	F_{max}	B_p	ω_n	LCOE
Humboldt Bay, CA	Nominal	20	0.30	0.20	0.80	9e6	3.1e5	1.49	0.75
Humboldt Bay, CA	Optimized	20	0.30	0.10	0.52	60e6	8.2e5	0.54	0.02
PacWave North, OR	Optimized	20	0.30	0.10	0.50	61e6	8.2e5	0.55	0.01
PacWave South, OR	Optimized	21	0.29	0.10	0.49	67e6	8.5e5	0.55	0.01
WETS, HI	Optimized	17	0.35	0.10	0.59	23e6	6.2e5	0.62	0.05

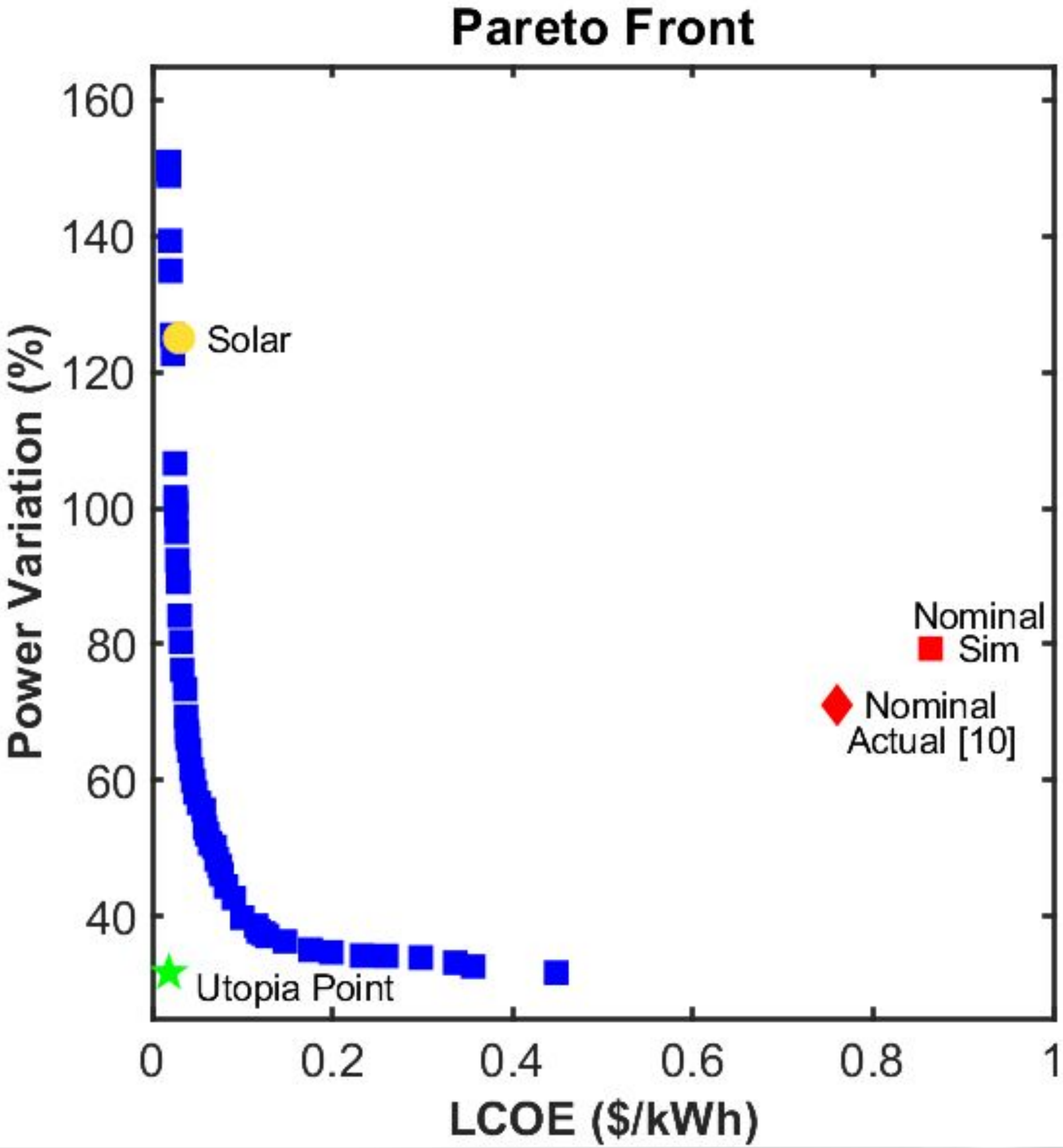
- Optimal design consistent across the west coast
- Hawaii requires slightly smaller float and submerged spar for optimality
- Using California design in Hawaii increases LCOE by 5% compared to optimal

Multiobjective Optimization

Pattern search algorithm

Tradeoff: low LCOE possible at the cost of high power variation

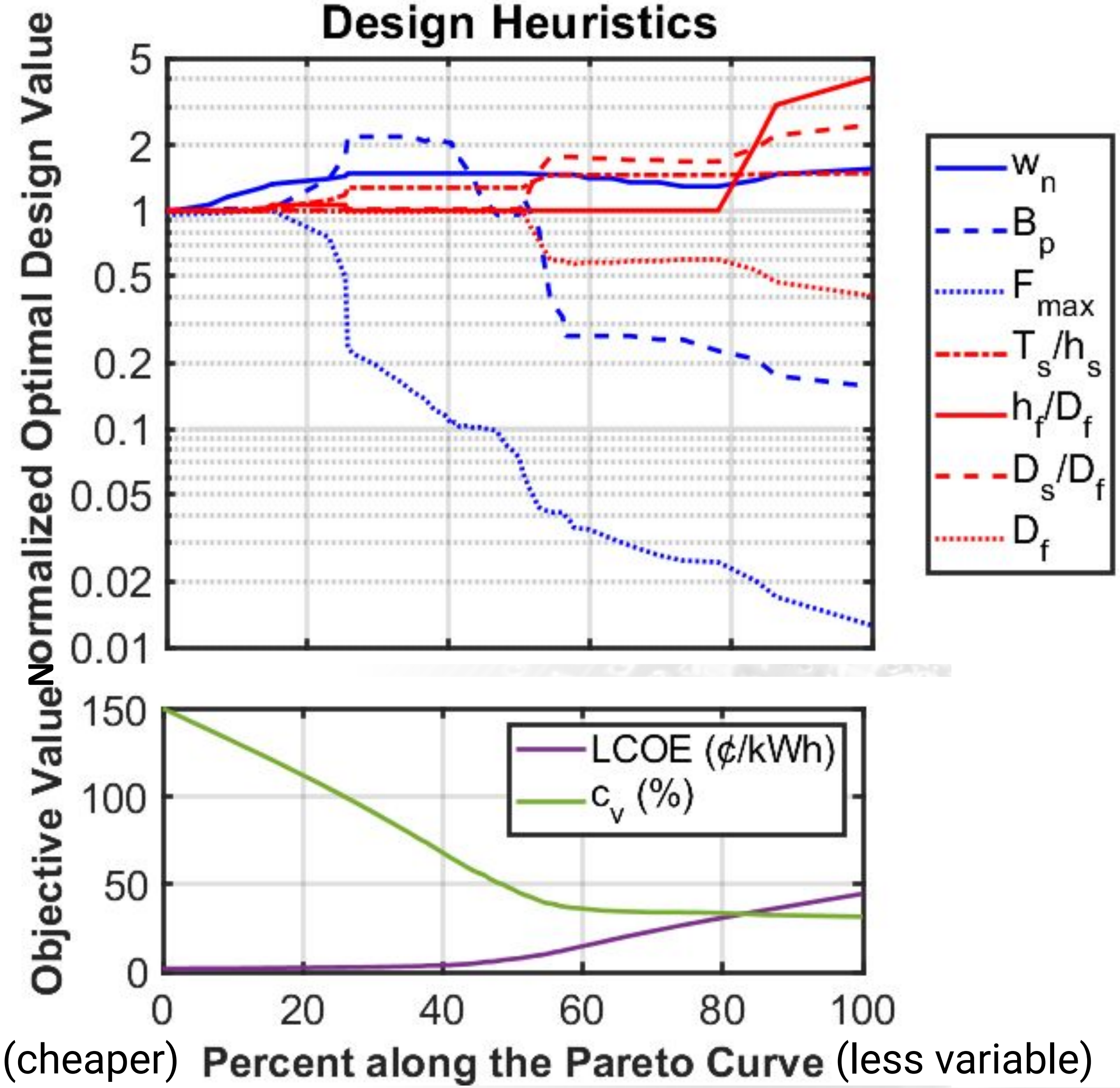
Diminishing returns as solution approaches single-objective optimal



Design Takeaways

The optimal value of geometric design variables remain relatively constant, while control design variables tend to vary across the pareto front.

This may allow a **single hardware design** across applications.

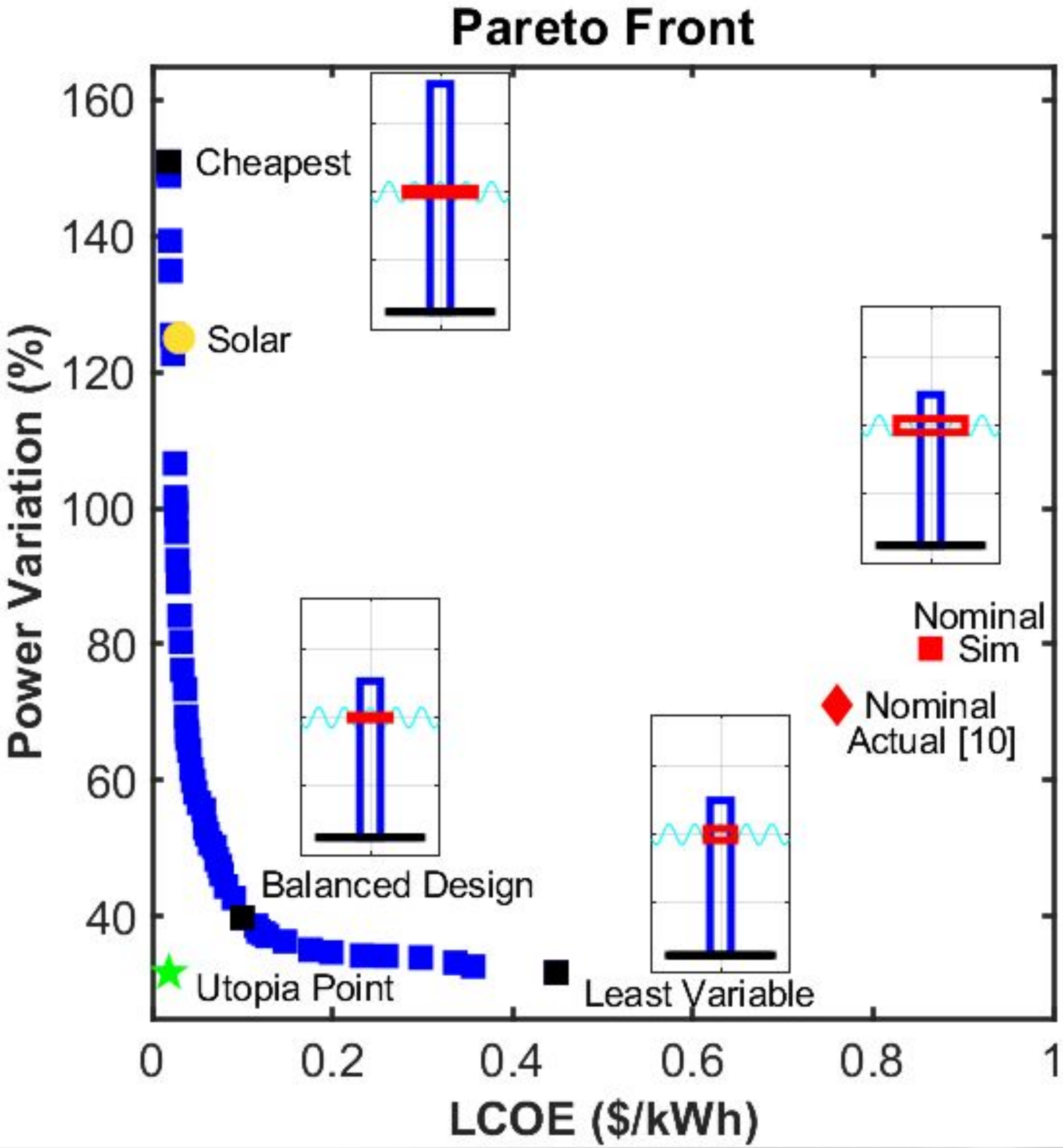


Representative Designs

Applications with cheap, abundant energy storage:
Minimum LCOE design

Applications with expensive but available energy storage:
Balanced design

Applications with extremely limited energy storage:
Minimum variation design



Conclusions

- Multidisciplinary Design Optimization framework applied to the RM3 WEC
- Achieved **40 x lower LCOE** and 2 x lower c_v
- Optimal pareto tradeoff curve with three representative designs
- High **sensitivity** to sea states and economic parameters
- Potential to **share hardware** designs across applications

Future Work

1. Improve simulation fidelity
   a. BEM integration for hydrodynamic coefficients
   b. More complex controllers
2. Consider application-specific objective functions
3. Extend to other WEC architectures

References

[1] Lehmann, M., Karimpour, F., Goudey, C. A., Jacobson, P. T., and Alam, M.-R., 2017. “Ocean wave energy in the united states: Current status and future perspectives”. Renewable and Sustainable Energy Reviews, 74, pp. 1300– 1313.
[2] LiVecchi, A., Copping, A., Jenne, D., Gorton, A., Preus, R., Gill, G., Robichaud, R., Green, R., Geerlofs, S., Gore, S., Hume, D., McShane, W., Schmaus, C., and Spence, H.,2019. Powering the blue economy: Exploring opportunities for marine renewable energy in maritime markets. Tech. rep., US Department of Energy, Apr.
[3] Aderinto, T., and Li, H., 2018. “Ocean Wave Energy Converters: Status and Challenges”. Energies, 11(5), May, p. 1250.
[4] Agte, J., de Weck, O., Sobieszczanski-Sobieski, J., Arendsen, P., Morris, A., and Spieck, M., 2009. “MDO: Assessment and direction for advancement—an opinion of one international group”. Structural and Multidisciplinary Optimization, 40(1), Apr., p. 17.
[5] Martins, J. R. R. A., and Lambe, A. B., 2013. “Multidisciplinary Design Optimization: A Survey of Architectures”. AIAA Journal, 51(9), Sept., pp. 2049–2075.
[6] Al Shami, E., Wang, X., Zhang, R., and Zuo, L., 2019. “A parameter study and optimization of two body wave energy converters”. Renewable Energy, 131, Feb., pp. 1–13.
[7] Herber, D., 2014. “Dynamic system design optimization of wave energy converters utilizing direct transcription”. PhD thesis, 05.
[8] Gaudin, C., David, D. R., Cai, Y., Hansen, J. E., Bransby, M. F., Rijnsdorp, D. P., Lowe, R. J., O’Loughlin, C. D., Lu, T., and Uzielli, M., 2021. “From single to multiple wave energy converters: Cost reduction through location and configuration optimisation”. Final Report. The University of Western Australia.
[9] Goteman, M., Engstr ¨ om, J., Eriksson, M., Isberg, J., and ¨ Leijon, M., 2014. “Methods of reducing power fluctuations in wave energy parks”. Journal of Renewable and Sustainable Energy, 6(4), July, p. 043103.
[10] Neary, V. S., Previsic, M., Jepsen, R. A., Lawson, M. J., Yu, Y.-H., Copping, A. E., Fontaine, A. A., Hallett, K. C., and Murray, D. K., 2014. Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies. Tech. Rep. SAND2014-9040, Sandia National Laboratories, Albuquerque, New Mexico, Mar.
[11] Falcao, A. F. d. O., 2010. “Wave energy utilization: A re- ˜ view of the technologies”. Renewable and Sustainable Energy Reviews, 14(3), Apr., pp. 899–918.
[12] Newman, J. N., 1977. Marine Hydrodynamics. Aug.
[13] Franklin, G., Powell, J., and Emami-Naeini, A., 2015. “Equivalent Gain Analysis Using Frequency Response: Describing Functions”. In Feedback Control of Dynamic Systems, seventh ed. Pearson, pp. 678–682.
[14] , 2020. System Advisor Model (SAM). National Renewable Energy Laboratory, Nov.
[15] Paretosearch Algorithm - MATLAB & Simulink. https://www.mathworks.com/help/gads/paretosearchalgorithm.html.
[16] Boretti, A., 2020. “High-frequency standard deviation of the capacity factor of renewable energy facilities: Part 1—Solar photovoltaic”. Energy Storage, 2(1), p. e101.

Learn more:

MATLAB code available open source
Updated paper to be posted shortly
https://github.com/symbiotic-engineering/MDOcean/

Rebecca McCabe
rgm222@cornell.edu

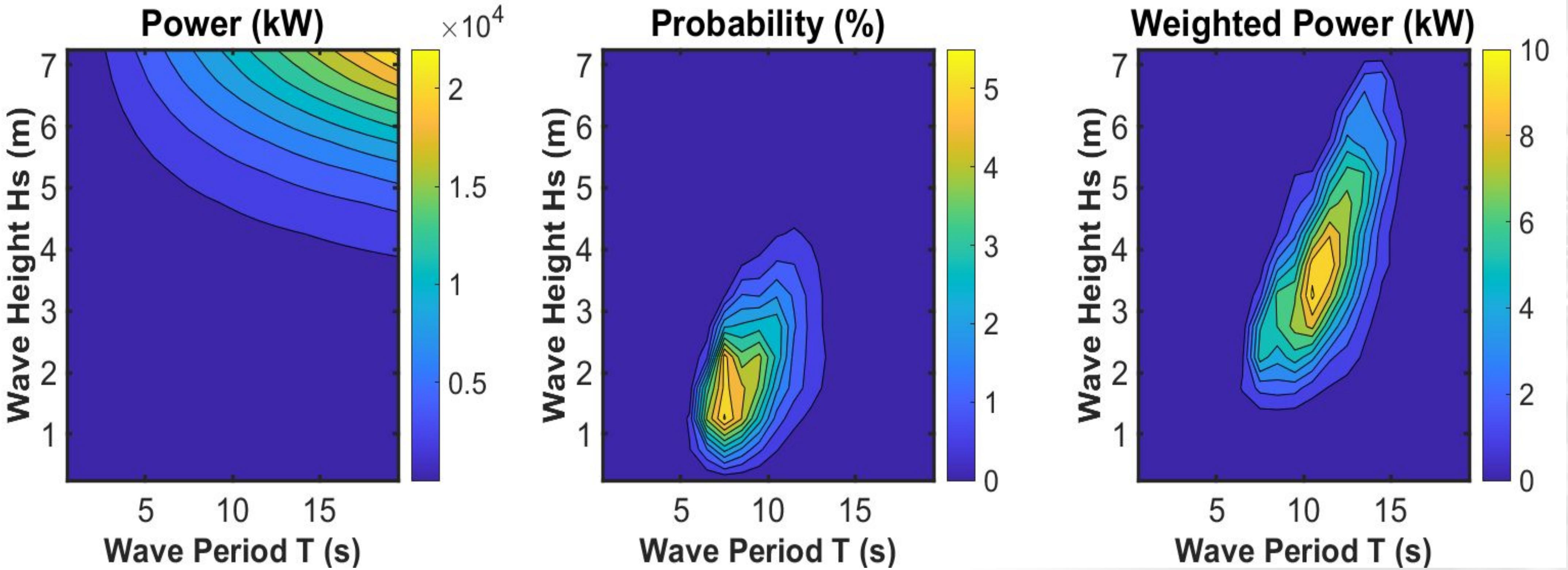
Funding Sources:

This material is based upon work supported by the **National Science Foundation** Graduate Research Fellowship under Grant No. DGE–2139899, and the **Cornell Engineering Fellowship**. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors(s) and do not necessarily reflect the views of the National Science Foundation.

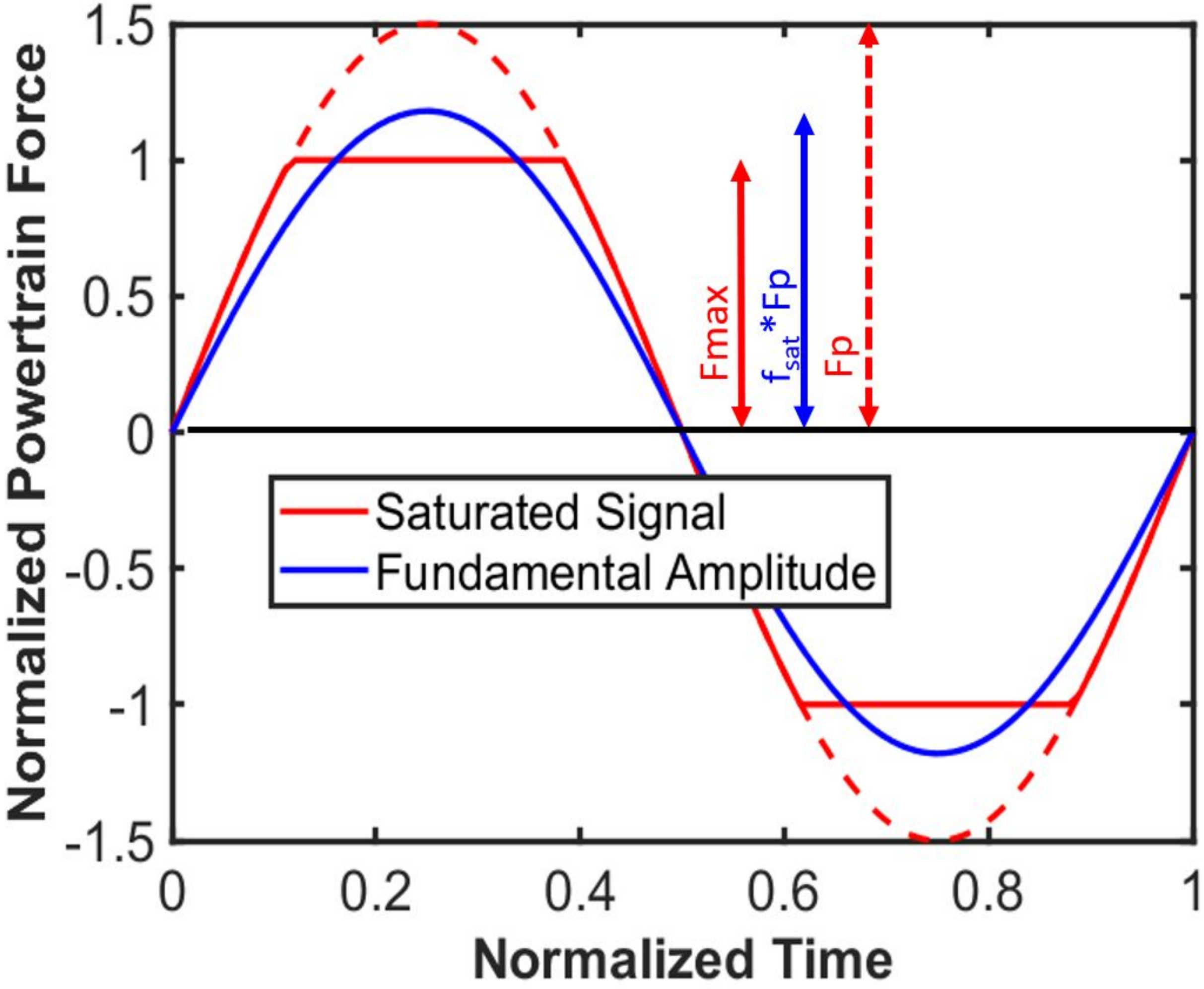
Modeling and Simulation

Device Power Capability * **Site Wave Data** = **Power Production**

From Simulation | *JPD for Humboldt, CA*



Force Saturation with Describing Functions



Approximate the saturated signal with its fundamental amplitude

Power Distribution Comparison