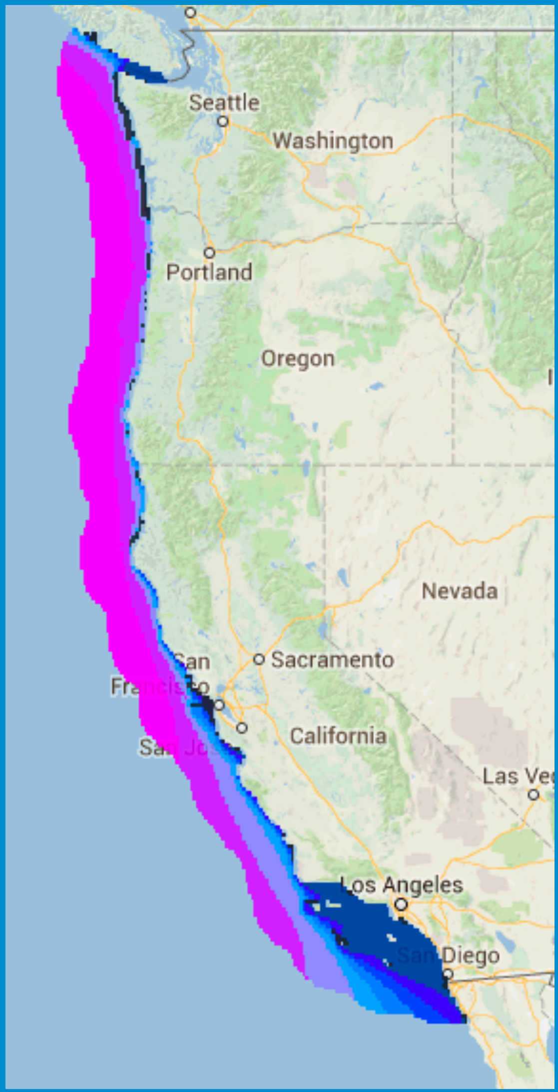

Wave Energy in the United States and Numerical Modeling of Wave Energy Conversion Devices

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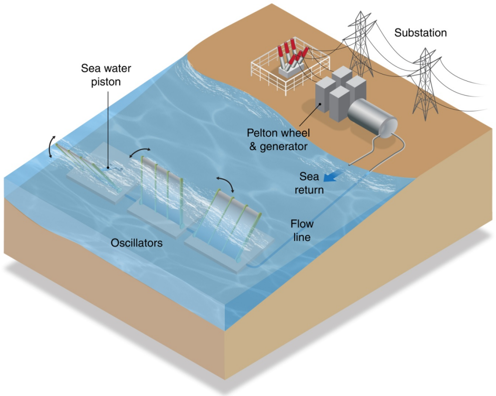
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Presentation outline

Wave energy and the US resource

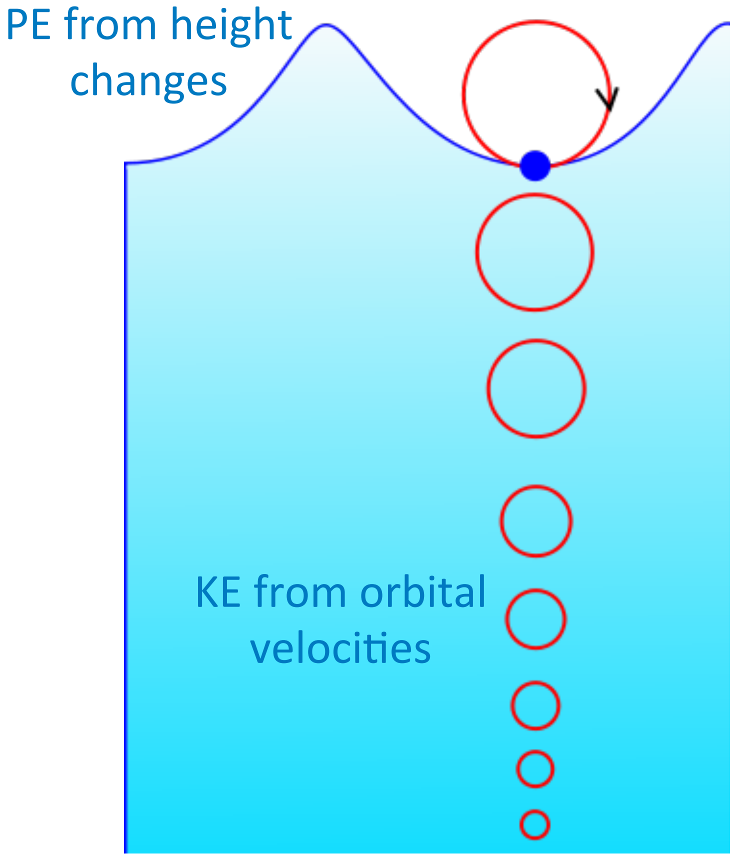
Wave energy conversion (WEC) devices



NREL's numerical modeling efforts

Removed proprietary data

Wave energy is the combination of kinetic and potential energy in a propagating wave front

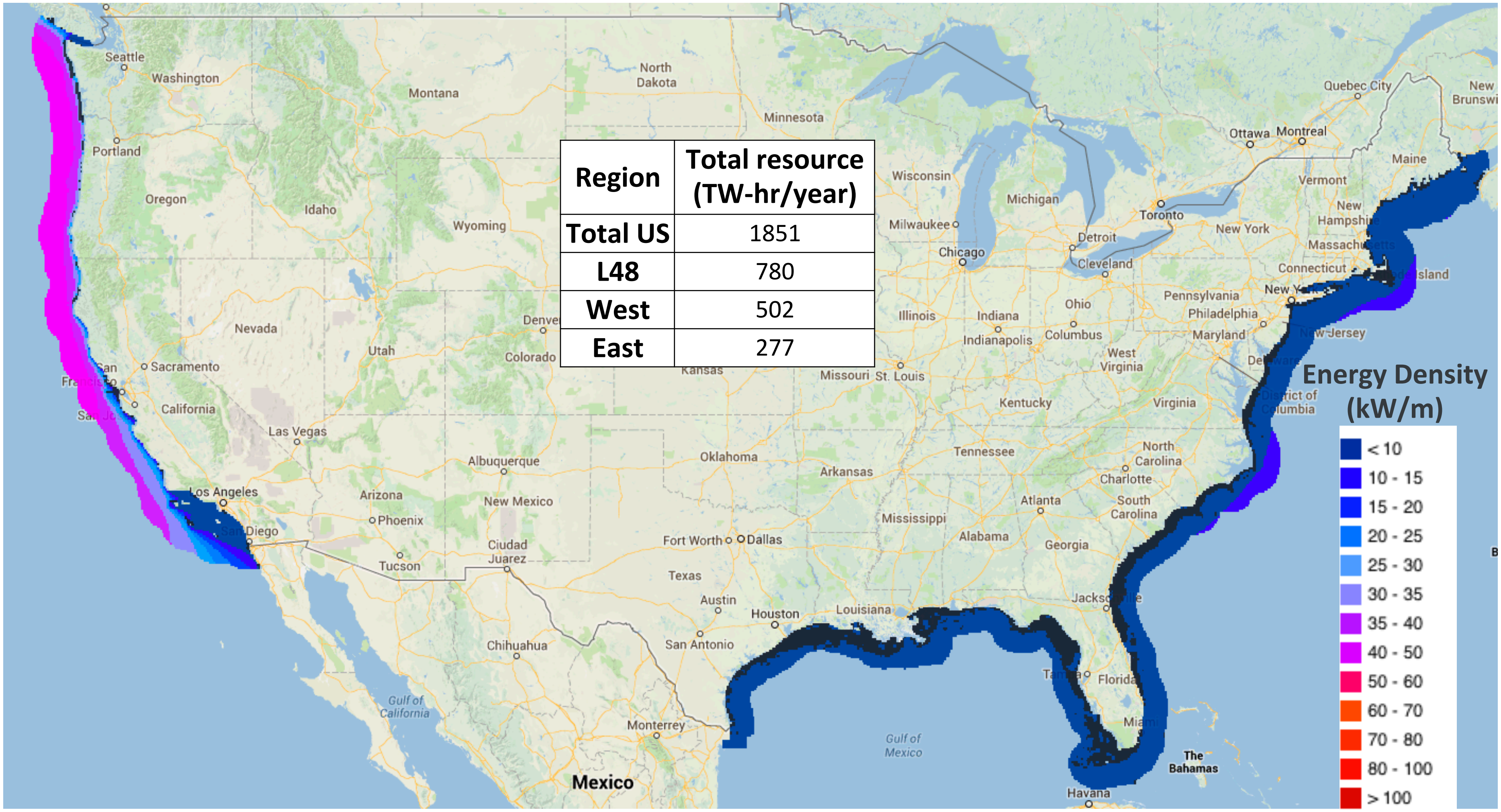


Relevant wave properties (e.g. velocity, pressures, etc.) can be derived using Stokes wave theory

The wave power per unit wave crest in deep water is:

$$P = \frac{\rho g^2}{64} H^2 T \; [\frac{W}{m}]$$

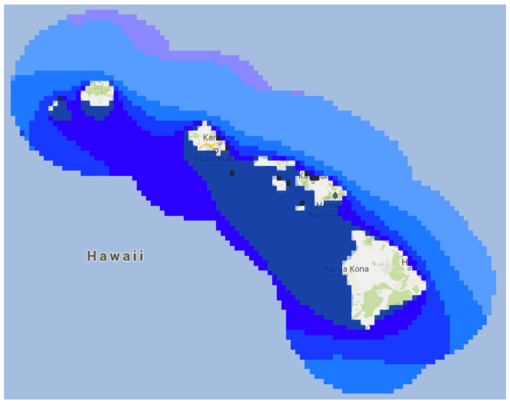
Wave resource assessment: In the lower 48 states, the wave resource is concentrated in the pacific northwest



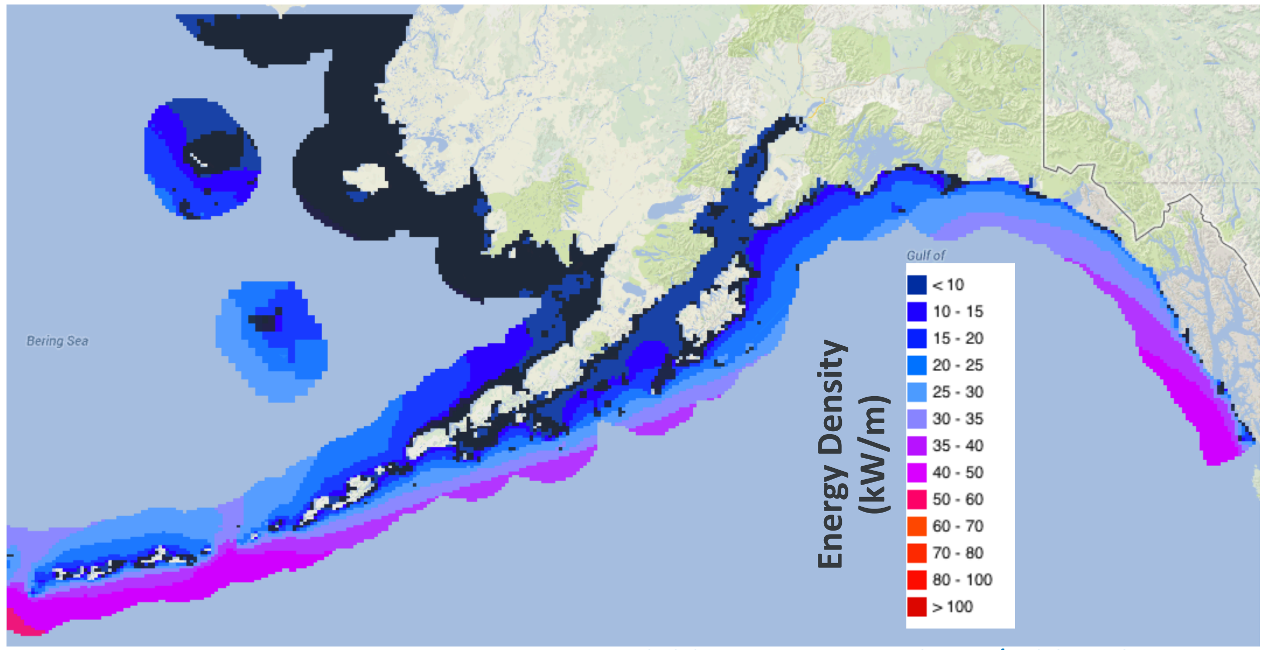
Region	Total resource (TW-hr/year)
Total US	1851
L48	780
West	502
East	277

For reference: 2011 US generation = 4100 TW-hr
Map available at: maps.nrel.gov/mhk_atlas

Alaska and Hawaii have enough wave energy to satisfy their state electricity needs many times over



Region	Total resource (TW-hr/year)
Total US	1851
Alaska	973
Hawaii	98



Map available at: maps.nrel.gov/mhk_atlas

Exporting power to the L48 would be very difficult → transmission is prohibitively expensive

For reference: 2011 US generation = 4100 TW-hr

Wave energy has the potential to make significant contributions to US electricity generation needs

US Energy Information Agency estimates that the 2050 US electricity generation will be **5225 TW-hr**

The wave resource of the lower 48 states is equivalent to 15% of anticipated 2050 generation

Wave energy resource at the 100m depth contour

Region	Total resource (TW-hr/year)	% of 2050 US generation
Total US	1851	35.4%
L48	780	14.9%
West	502	9.6%
East	277	4.3%
Alaska	973	18.6%
Hawaii	98	1.9%

Environmental concerns and wave energy density determines how much energy can be practically extracted

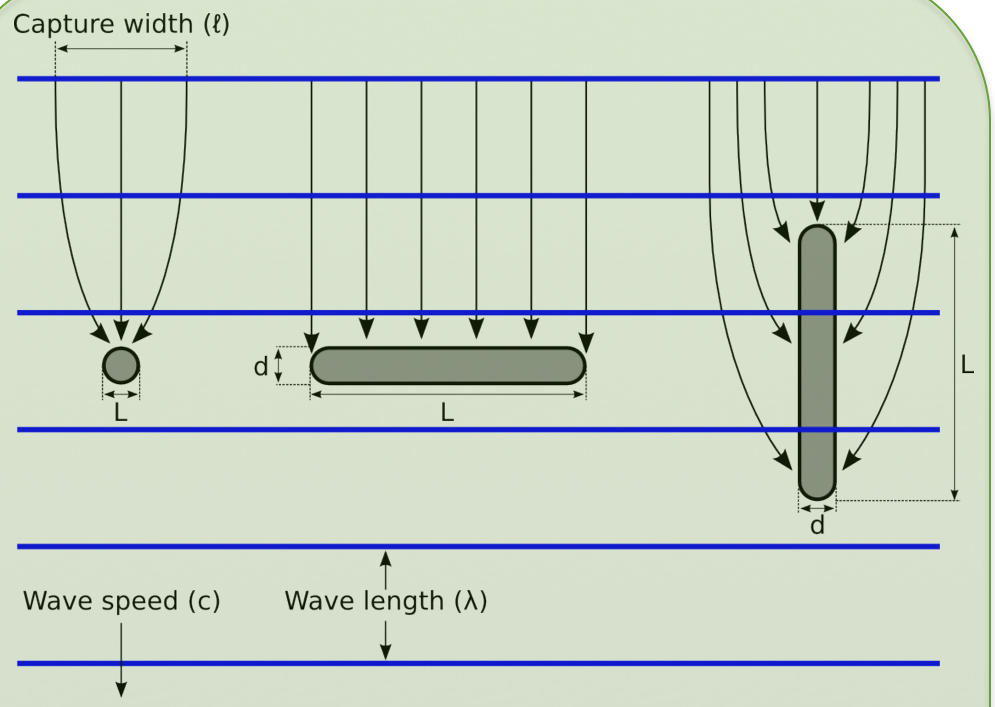
Green = marine sanctuary

Practically extractable wave energy

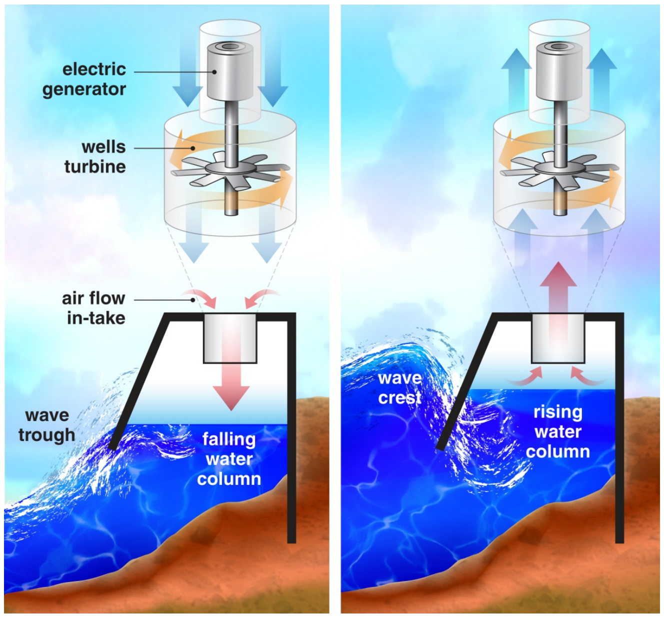
Region	Practical resource (TW-hr/year)	% of 2050 US generation
US	1022	19.6%
L48	495	9.5%
West	350	6.7%
East	145	2.8%
Alaska	461	8.8%
Hawaii	66	1.3%

Wave energy converters (WECs) are divided into four categories

NREL's numerical modeling focus



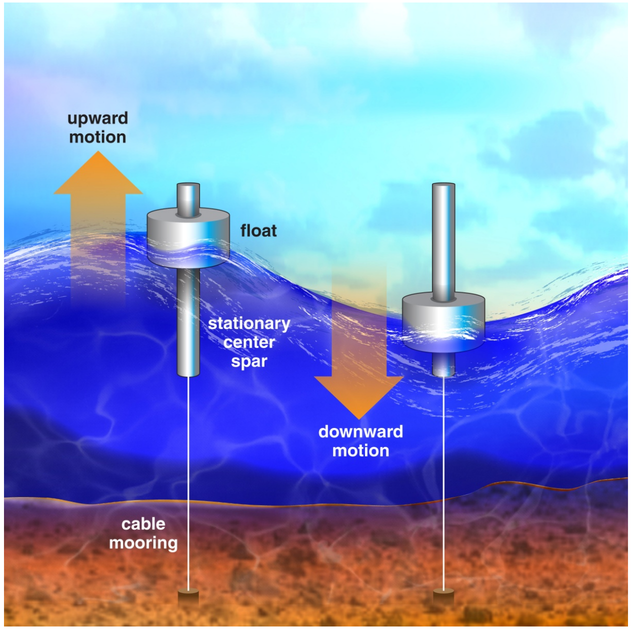
Point absorber **Terminator** **Attenuator**



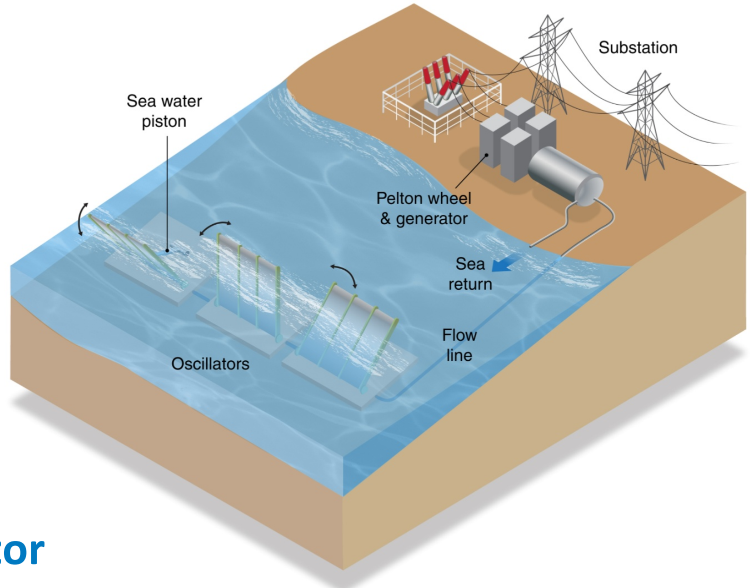
Oscillating water column

How do the current generation of WECs function?

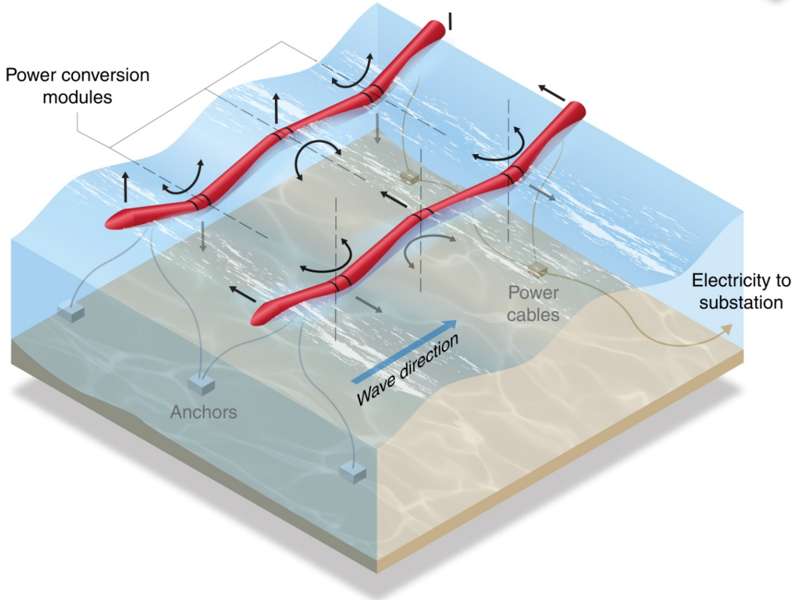
Point absorber



Terminator



Attenuator



WECs are being developed by several companies

Design loads are not well understood:

- High capital costs
- Unexpected failures

Device configuration for optimal power/cost ratio is unknown

WECs are not yet cost-competitive with other renewable technologies

NREL is developing numerical design and analysis tools to help the industry

Removed proprietary data

Simulating devices in operational and extreme conditions is a critical step in the design process

Removed proprietary data

Photos and videos provided by NREL partner Columbia Power Technologies

Operational: fluid-structure interactions are linear

Removed proprietary data

NREL is combining multi-body simulation capabilities with potential flow hydrodynamics to produce an open-source WEC design tool

A reduced order (i.e. linear) mathematical model for WECs in operational conditions

Determined using potential flow frequency domain analysis

$$(M + m_A)\ddot{X} = F_{EX} - F_{RD} + F_{HS} + F_V + F_{PTO}$$

- $(M + m_A)$: Body Mass & Added Mass Coefficient
- $\ddot{X}$: Acceleration
- F_{EX}: Wave Excitation Force
- F_{RD}: Radiation Damping Force
- F_{HS}: Hydrostatic Force
- F_V: Viscous Force
- F_{PTO}: PTO Force

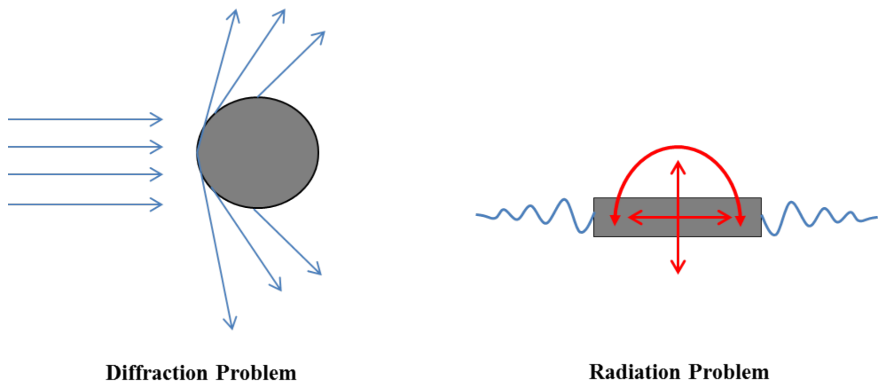
Key assumptions:

- **Small amplitude motion**
- **Linear waves only**
- **No overtopping or slamming**

Numerical implementation of the mathematical model

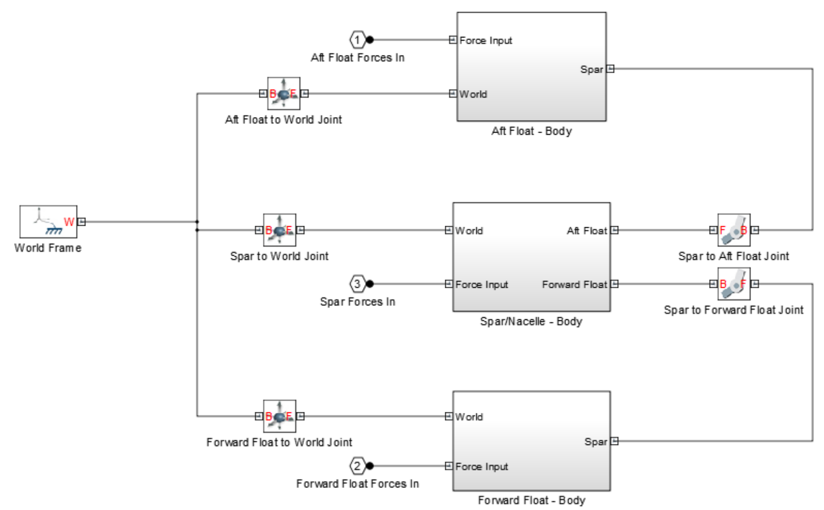
WAMIT frequency domain potential flow solver → a preprocessing step to determine:

- Excitation force
- Radiation damping force
- Added mass
- Hydrostatic force



SimMechanics → a time-domain multi-body dynamics solver implemented in MATLAB

- Block diagram format
- Easy integration with Simulink for PTO system simulation and control



Numerical results were compared to experimental wave tank data provided by Columbia Power Technologies

Removed proprietary data

Extreme/Survival: highly non-linear fluid-structure interactions make numerical modeling difficult

Removed proprietary data

NREL is exploring the possibility of using and developing Smooth Particle Hydrodynamics (SPH) for extreme load predictions

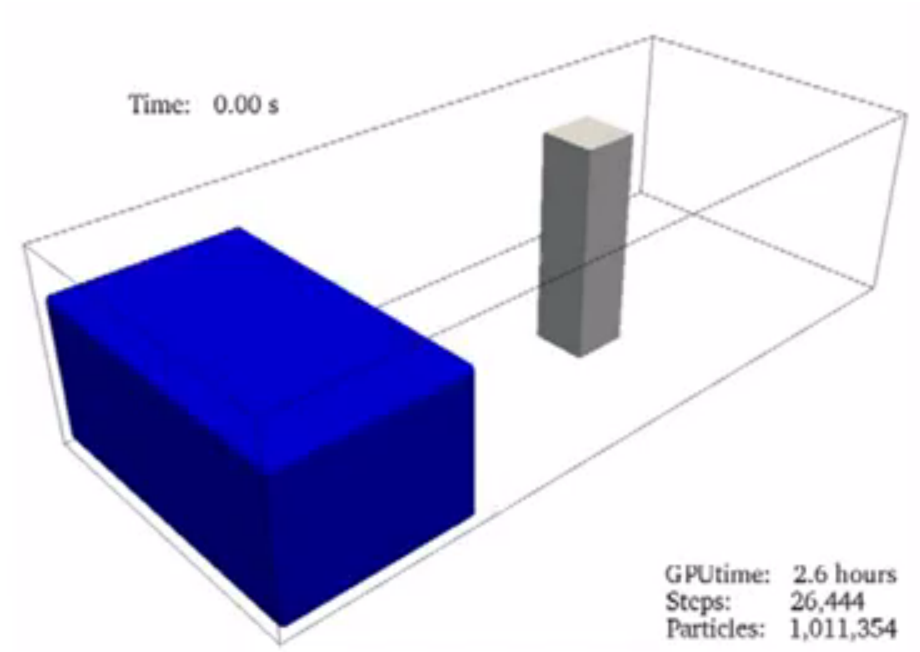
SPH models the Navier-Stokes equations using a set of Lagrangian particles

Advantages of SPH:

- WEC geometry easily resolved
- Modeling large amplitude WEC motions and complex non-linear free-surface phenomena is trivial

Existing SPH methods <u>cannot</u> model complex WEC devices because of multiply connected bodies, moorings, PTO, etc.

Ultimate goal: integrate SPH and multi-body-dynamics solver to facilitate accurate loads estimates



www.dual.sphysics.org

SPH formulation

Navier-Stokes equations:

$$\frac{D\rho}{Dt} = -\rho\nabla\vec{V} \longrightarrow \frac{D\rho_i}{Dt} = \sum_j m_j \vec{V}_{ij} \nabla_i W_i$$

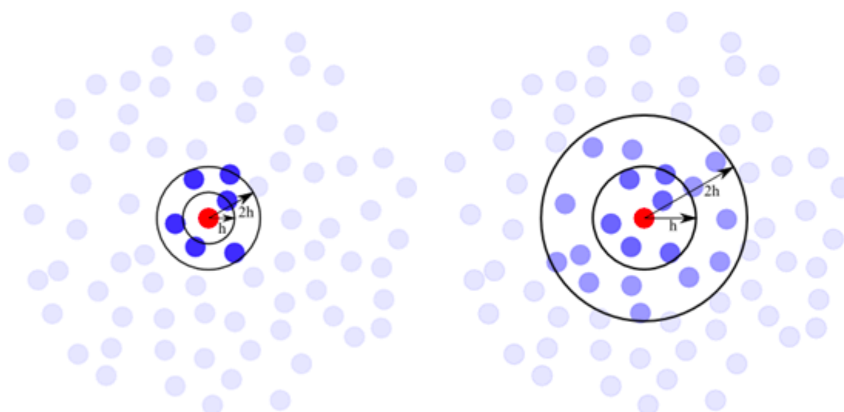
$$\frac{D\vec{V}}{Dt} = -\frac{1}{\rho}\nabla P + \vec{g} + \mu\nabla^2\vec{V}$$

Solved using explicit time integration methods

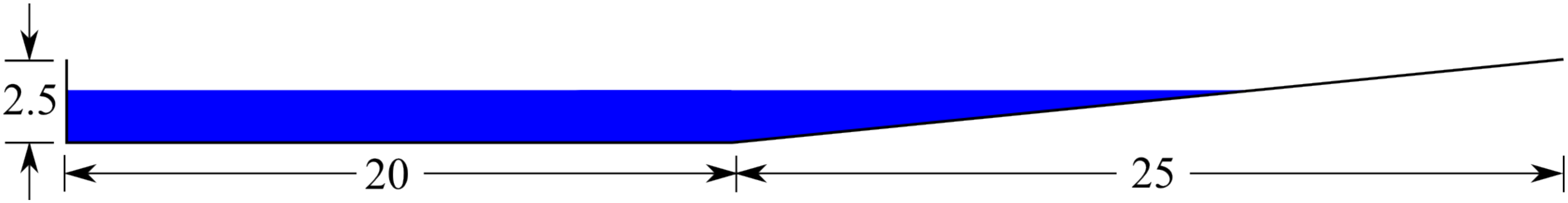
Kernel function:
Properties of each particle at time n+1 determined using averaging kernel across particles at time n

$$W_{ij} = \frac{10}{7\pi^2}\begin{cases} 1 - \frac{3}{2}q^2 + \frac{3}{4}q^3 & 0 \leq q \leq 1 \\ \frac{1}{4}(2-q)^3 & 1 < q < 2 \\ 0 & q \geq 2 \end{cases}$$

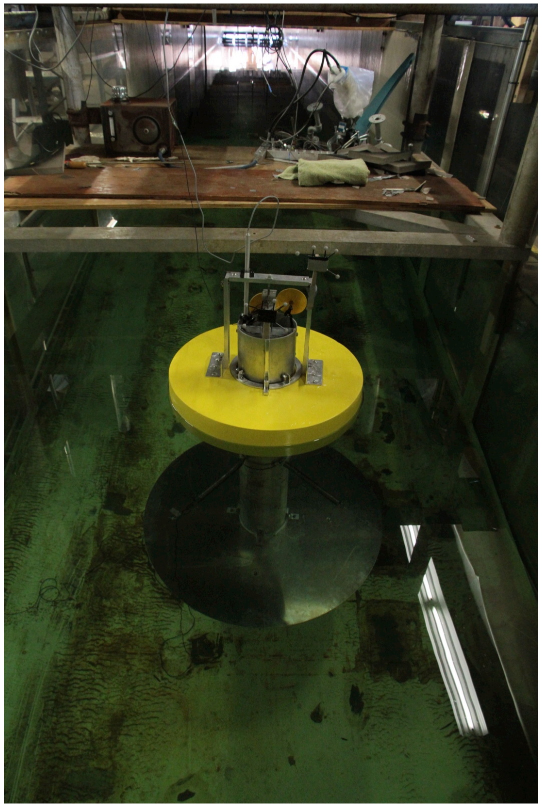
$$q = \frac{|\vec{r_{ij}}|}{h}$$



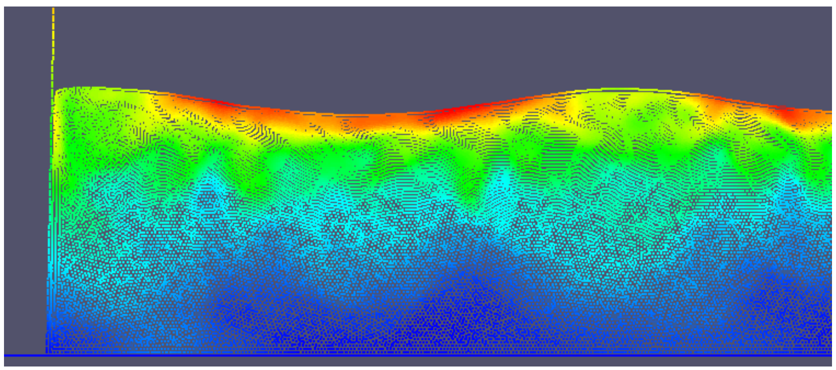
SPH is being used to simulate experiments NREL performed at SCRIPPS/UCSD



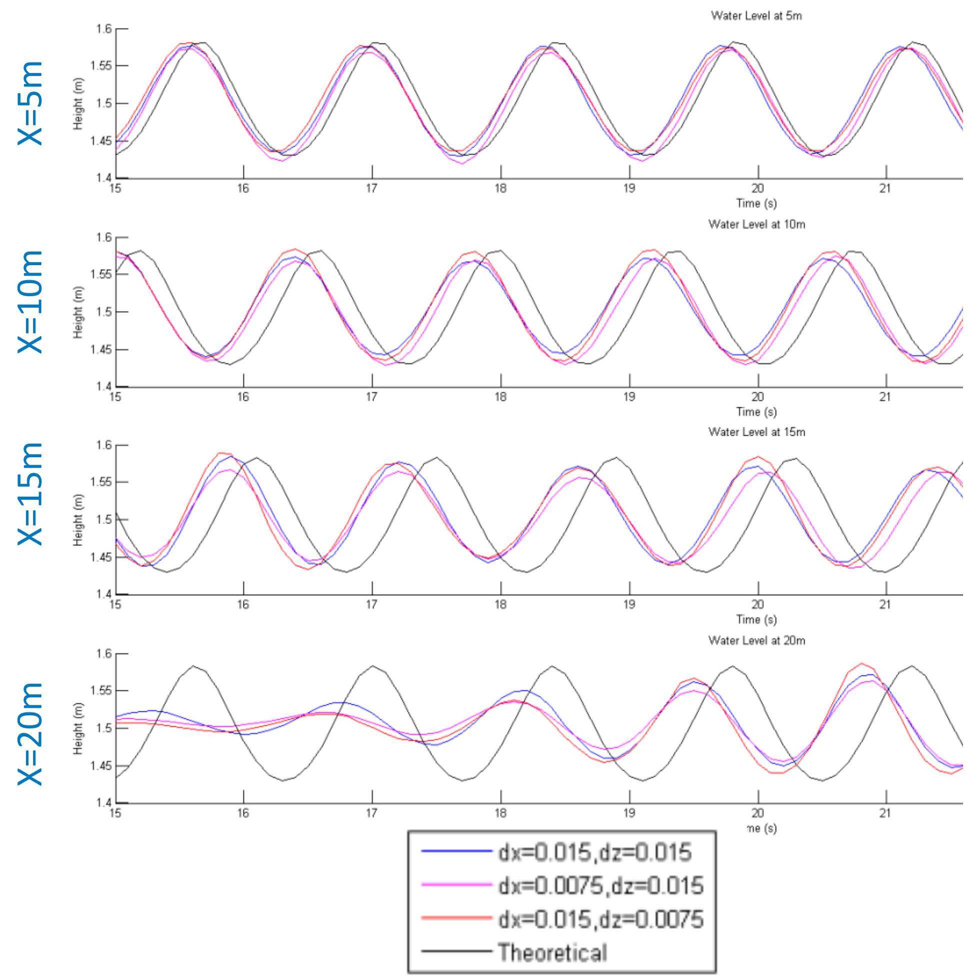
Dimensions in meters



First step: Simulate the wave maker and wave propagation in the SCRIPPS wave tank



Comparison of numerical results with 1st order waves



Conclusions

The US has a substantial wave energy resource that can contribute to future electricity needs

NREL is developing numerical design tools to assist in the design of the next generation of WEC technologies → codes will be open-source and freely available to the WEC research and design community

Future work

NREL, Sandia, and DOE are planning an experimental testing campaign to provide open source experimental data for code validation

Development of open-source frequency domain hydrodynamics solver → crowd sourced coding

Further exploration of SPH methods for extreme load predictions