An Overview of PRIMED:

The Pacific Regional Institute for Marine Energy Discovery

Anthony Truelove MASc, P.Eng.

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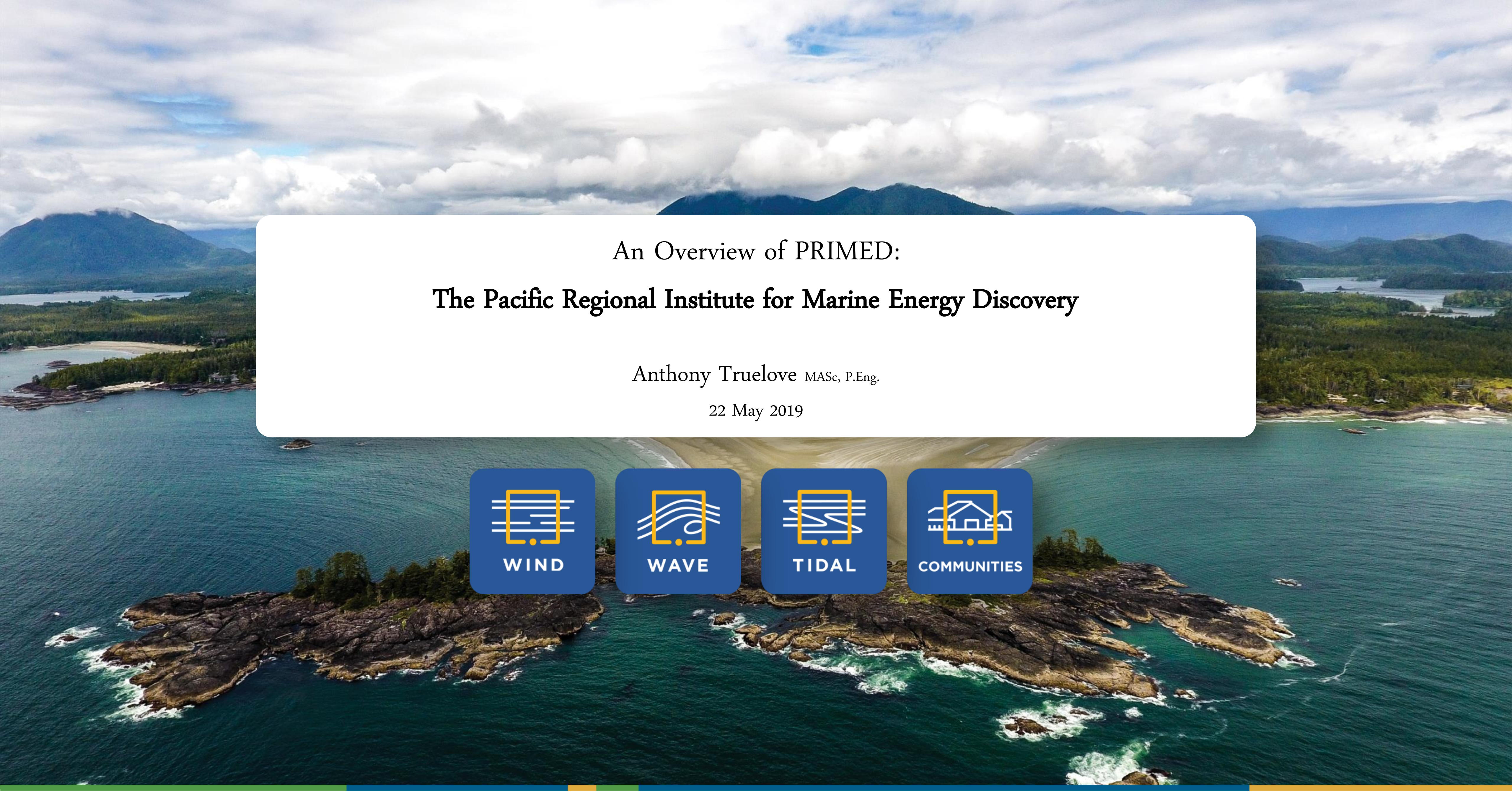


The Mission of PRIMED

It is the mission of PRIMED to accelerate the development and adoption of marine renewable energy technologies, including wind, wave, and tidal solutions. This is achieved by working with both communities and the private sector in order to identify the resources, assess the technology, and weigh the economics.

PRIMED

WIND

WAVE

TIDAL

COMMUNITIES

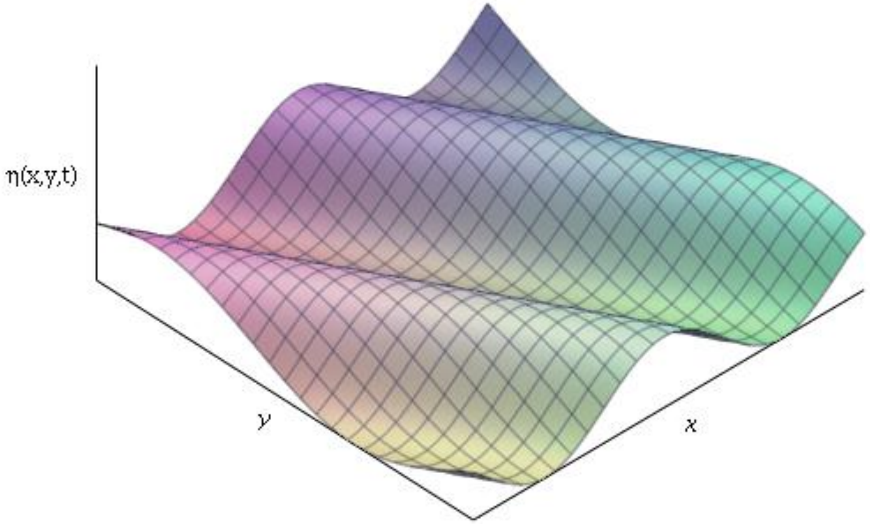
Overview

- Assessing Wave Energy Resources
- Modelling Wave Energy Converters
- Modelling Community Integration
- Example Case Study

Assessing Wave Energy Resources

Consider a planar wave traversing a flat, infinite sea. The sea surface elevation, $\eta(x,y,t)$, above some reference plane, can be described by

$$\eta(x,y,t) = a\cos(2\pi f t - k(x\cos(\theta) + y\sin(\theta)) + \phi)$$

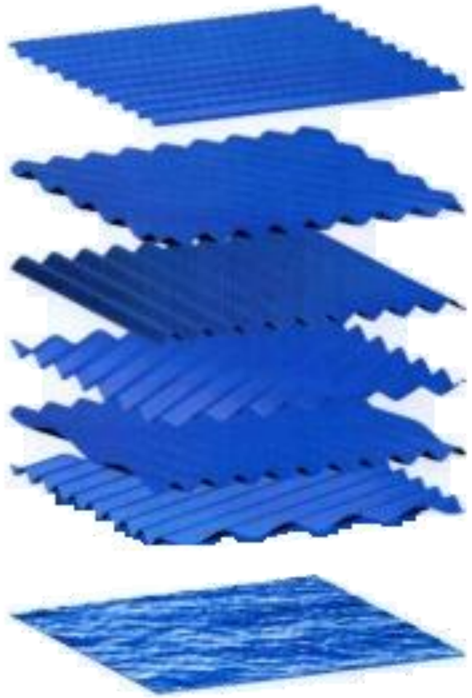


Planar wave

Assessing Wave Energy Resources

However, common experience tells us that a single, planar wave is generally not a suitable model for a realistic sea surface. Therefore, one might better model a realistic sea surface by way of a superposition of planar waves

$$\eta(x,y,t) = \sum_{i=1}^{\infty} a_i \cos(2\pi f_i t - k_i(x\cos(\theta_i) + y\sin(\theta_i)) + \phi_i)$$



Superposition of planar waves

Assessing Wave Energy Resources

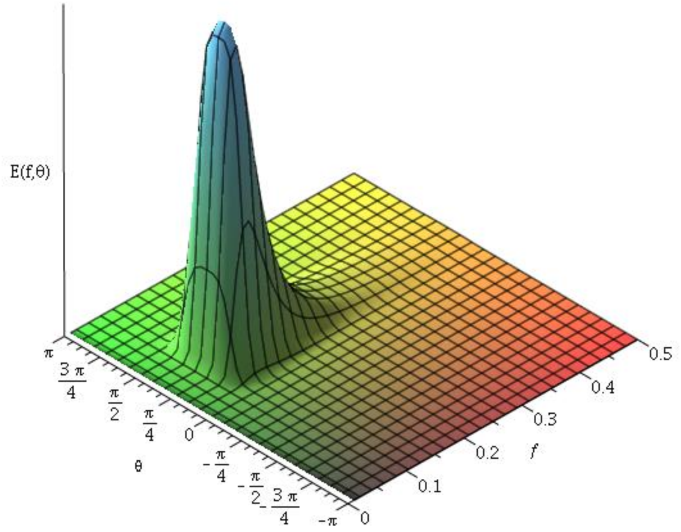
With respect to the potential wave power transport along a given sea surface, one might introduce a directional variance density spectrum, $E(f,\theta)$, defined at a point (x,y) and for a time interval $t \in [0,T]$, such that

$$\mathrm{var}[\eta] = \int_0^{2\pi}\int_0^{\infty} E(f,\theta)\,df\,d\theta$$

with $E(f,\theta)$ generally being given by $E(f)D(\theta)$. From this, the potential wave power transport (power per unit capture width) for deep water waves can be computed by way of

$$J = \frac{1}{2}\rho g \int_0^{2\pi}\int_0^{\infty} c_g(f,\theta)E(f)D(\theta)\,df\,d\theta$$

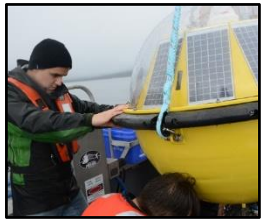
where $c_g(f,\theta)$ is wave group velocity.



Example directional variance density spectrum [rad, Hz]

Assessing Wave Energy Resources

In practice, the directional variance density spectrum for a given point and time interval is measured by way of a buoy deployment. In extension, the data collected from buoy deployments can be used as boundary conditions for sea surface modelling in the nearshore, where a simple superposition of planar waves in a flat, infinite sea ceases to be a suitable model. Perhaps the most commonly applied nearshore modelling technique is the Simulating Waves Nearshore (SWAN) model.



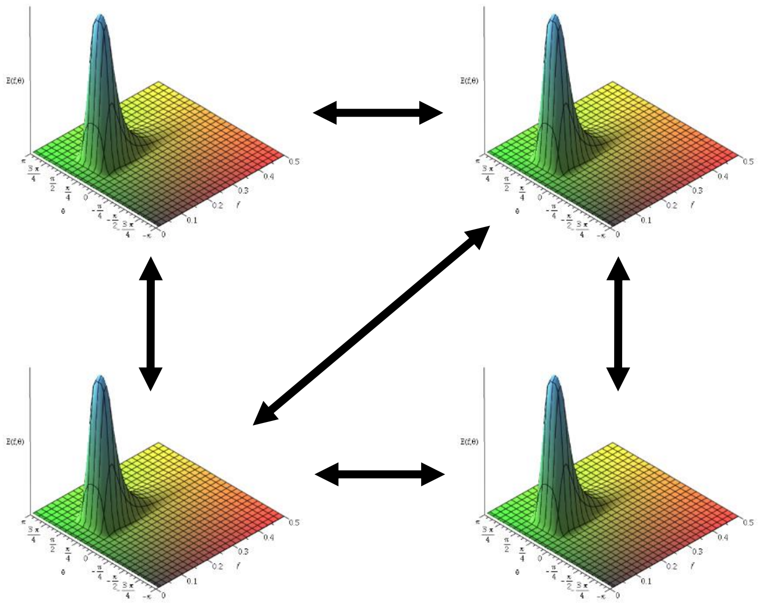
Deployment of Watchmate buoy

AXYS TECHNOLOGIES INC.

The SWAN model is essentially a convection-diffusion problem posed within and between variance density spectra over a discretization of an area of sea. The governing equations for this model are

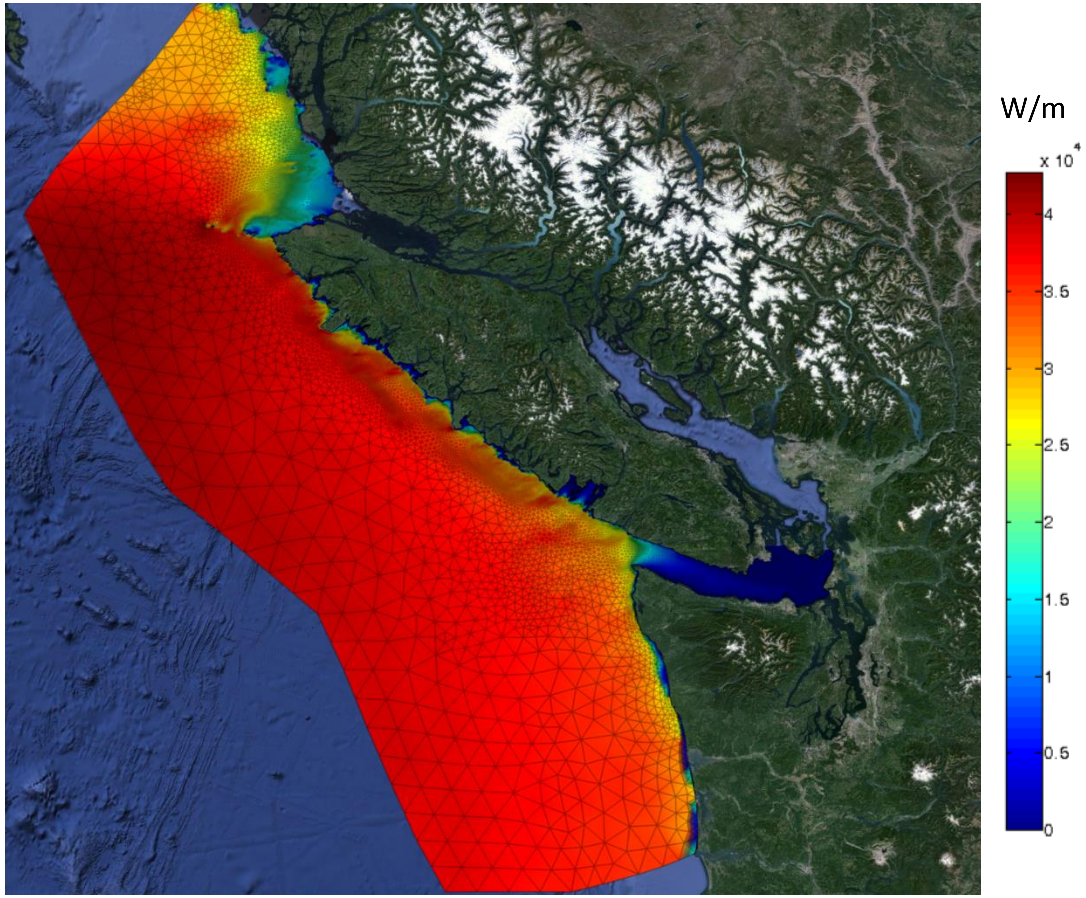
$$\frac{\partial N}{\partial t} + \nabla_{xy} \cdot \left[\left(\vec{c}_g + \vec{U}\right)N\right] + \frac{\partial}{\partial \sigma}(c_\sigma N) + \frac{\partial}{\partial \theta}(c_\theta N) = \frac{S_{\text{tot}}}{\sigma}$$

$$\text{where } N = \frac{E}{\sigma} \text{ and } \sigma = 2\pi f - \vec{k} \cdot \vec{U}$$



SWAN model, four node example

Assessing Wave Energy Resources

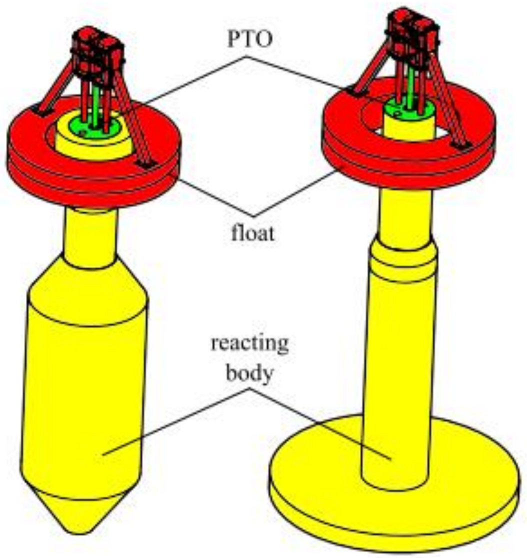


SWAN model, wave power transport (annual average) off Vancouver Island

Modelling Wave Energy Converters

Modelling a wave energy converter (WEC) consists of, essentially, two things

1. Generating a suitably representative sea surface; and,
2. Modelling the motion of the WEC due to the motion of the sea surface.



Example WEC design

Modelling Wave Energy Converters

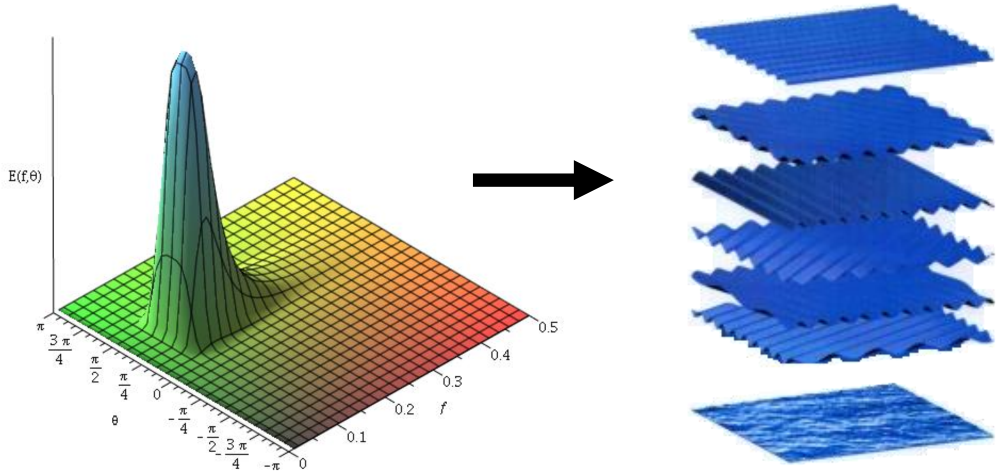
Generating a suitably representative sea surface can be achieved by way of constructing appropriate wave modes given a directional variance density spectrum. For instance, it can be shown that, for a superposition of cosine waves,

$$\mathrm{var}[\eta] = \int_0^{2\pi}\int_0^{\infty} E(f)D(\theta)\,df\,d\theta = \frac{1}{2}\sum_{i=1}^{\infty}\sum_{j=1}^{\infty} a_{i,j}^2$$

Therefore, one might choose

$$a_{i,j} = \sqrt{2E(f_i)D(\theta_j)(\Delta f)_i(\Delta\theta)_j}$$

together with random phases $\phi_{i,j}$, over an appropriate discretization of the (f,θ) domain.



Superposition of planar waves from variance density

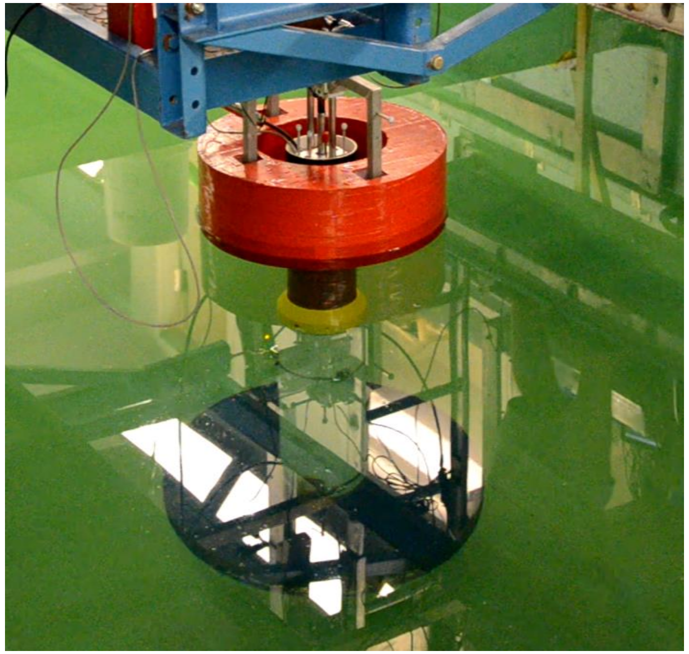
Modelling Wave Energy Converters

Given a generated sea surface, one can model the resulting WEC motion by way of applying Newton II

$$\mathbf{M}\ddot{x} = \underbrace{F_{\mathrm{FK}} + F_{\mathrm{s}} + F_{\mathrm{r}}}_{\text{hydrodynamics}} + F_{\mathrm{hs}} + F_{\mathrm{m}} + F_{\mathrm{PTO}}$$

It is the reaction force from the power take-off (PTO) which is indicative of the rate at which a WEC can extract energy from the sea.

The Froude-Krylov force (F_{FK}) is the force upon the WEC due to the dynamic pressure in the undisturbed wave modes. The scattering force (F_s) is the force due to the WEC body scattering the encountered wave modes. The radiation damping force (F_r) is the force due to the WEC motion generating new waves in the absence of any incoming wave modes.



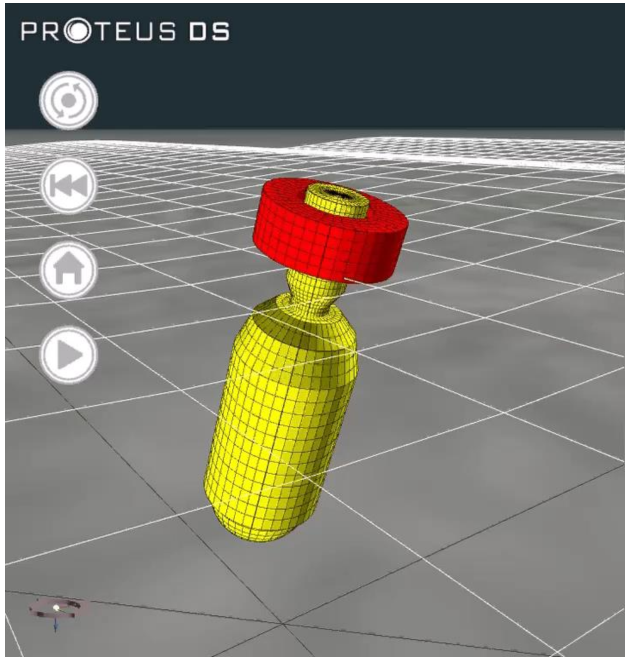
Example WEC (scale model) in motion

Modelling Wave Energy Converters

In practice, determining the motion of a WEC due to the motion of the sea surface is achieved by way of a finite element approach. The WEC geometry is discretized into a finite number of panel elements, and then the force of the sea upon each panel is integrated over the wetted surface of the WEC geometry in order to determine the net motion.

The sea and WEC modelling tool currently used at PRIMED is

PROTEUS DS

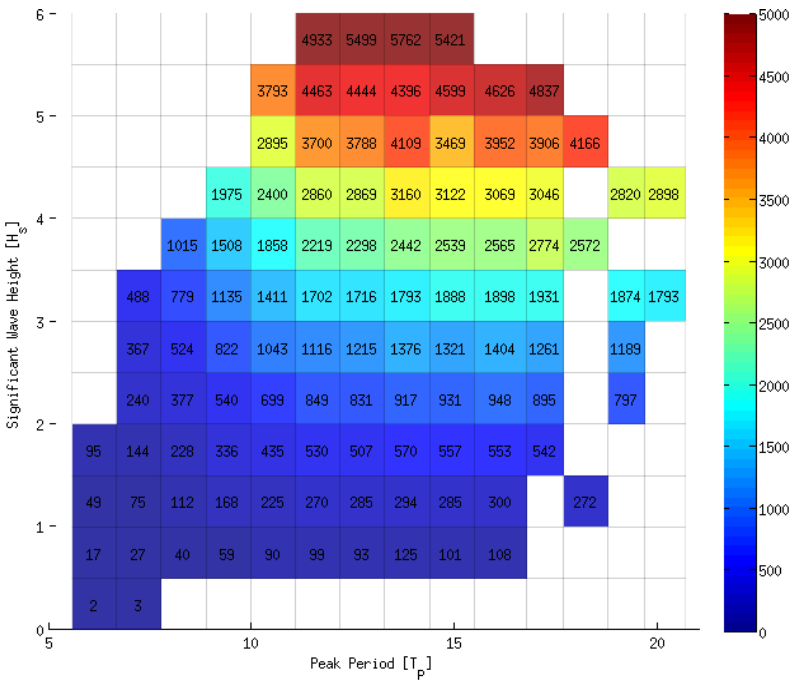


Modelled WEC motion

Modelling Wave Energy Converters

Given the ability to both generate sea surface motion and model the resulting WEC motion, one can begin to assess the expected performance of a particulate WEC design deployed in a particular sea. This expected performance is generally expressed by way of a performance matrix.

Significant wave height, H_s, and peak period, T_p, are parameters of the non-directional variance density spectrum $E(f)$.



Example WEC performance matrix [m, s, W]

Modelling Community Integration

In order to integrate a WEC into a community as an effective source of energy, one must first asses the local wave energy resource along with the corresponding WEC performance. This alone, however, is not sufficient, as the interaction of the WEC with the existing sources and loads of the community must be considered. Successful adoption of this technology will occur only if it is economical to do so.

Hot Springs Cove

Modelling Community Integration

In essence, the community integration problem is a constrained optimization problem whereby one seeks to satisfy the load of a given community, using an available set of sources, in a manner which minimizes the cost of satisfying the load. As such, the community integration problem can be summarized as follows

$$\text{Minimize:}\quad C_{\text{NPV}} = \sum_{i=1}^{n}\sum_{j=1}^{m} e(t_i)c_j(t_i)s_j(t_i)(\Delta t)_i$$

$$\text{Subject to:}\quad \left(\sum_{j=1}^{m} s_j(t_i)\right) - L(t_i) = 0 \;\; \forall i \in \{1, 2, \cdots, n\}$$

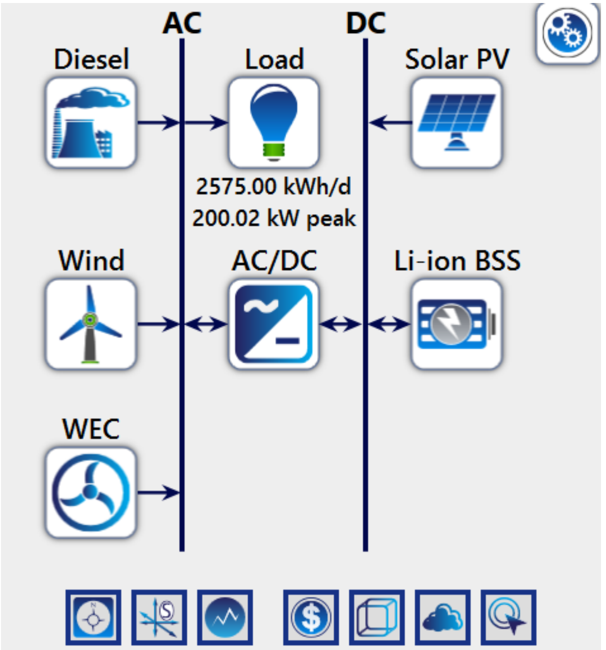
Modelling Community Integration

In practice, the community integration problem is handled using a comprehensive integration modelling tool which simultaneously captures grid dynamics, resource dynamics, economic considerations, etc. Such a tool allows the engineer to rapidly explore different community integration schemes in order to determine which is cost optimal.

The community integration modelling tools currently used at PRIMED are

HOMER Pro

RCOM



Example HOMER Pro grid

HOMER Energy

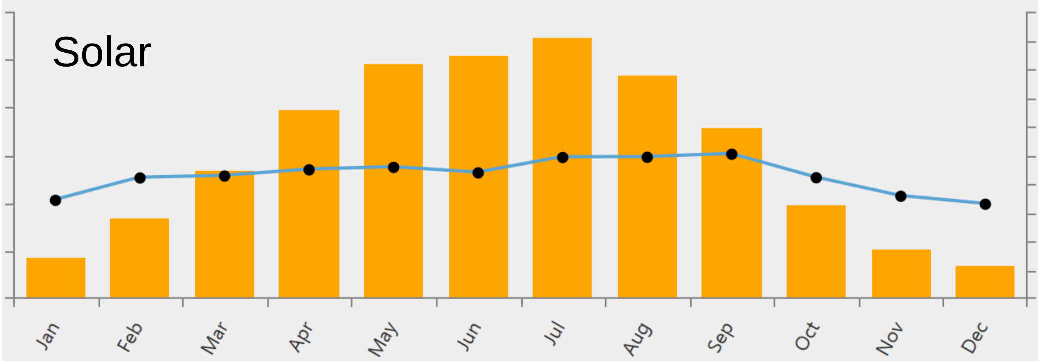
Example Case Study

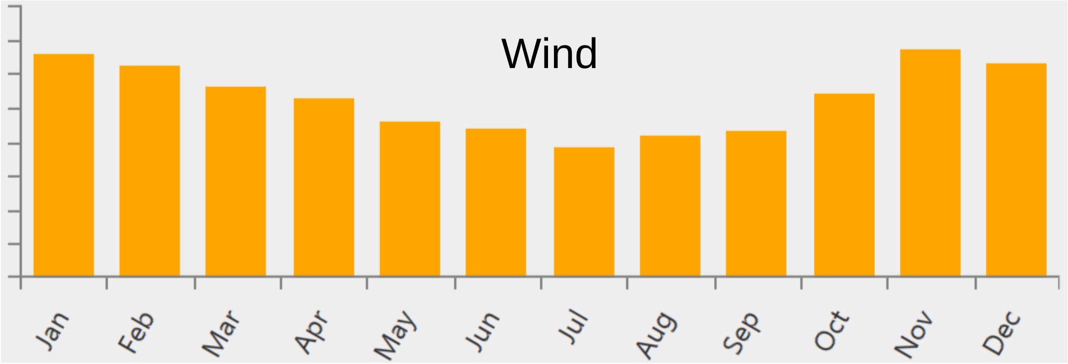
Suppose we wish to establish a remote community of 30 – 50 people on Spring Island (50° 00' 18" N 127° 25' 03" W), a small island off the north-west coast of Vancouver Island.

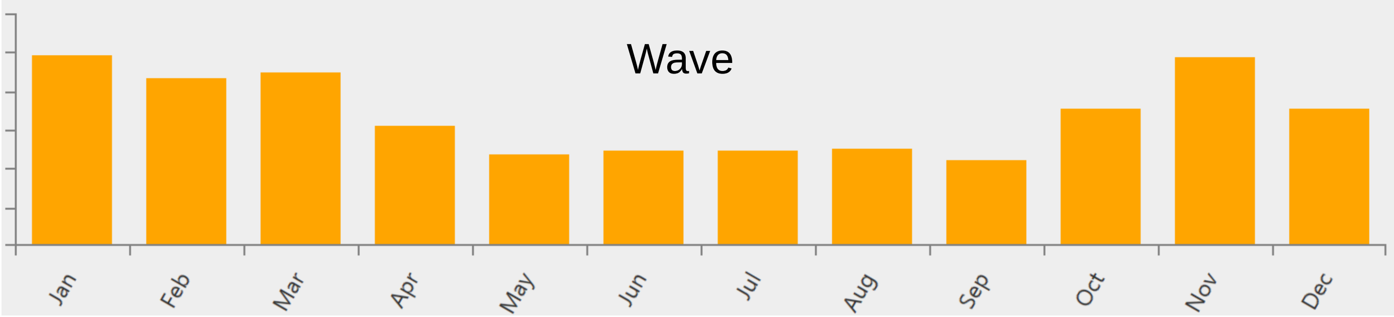
Assume local solar and wind resources of, on average, 0.125 kW/m^2 and 0.092 kW/m^2, respectively (derived from NASA data). From a SWAN model of the waters around Spring Island, one might also assume wave resources of, on average, 25 kW/m. Of course, these resources have seasonal variance.

Spring Island, BC

Example Case Study



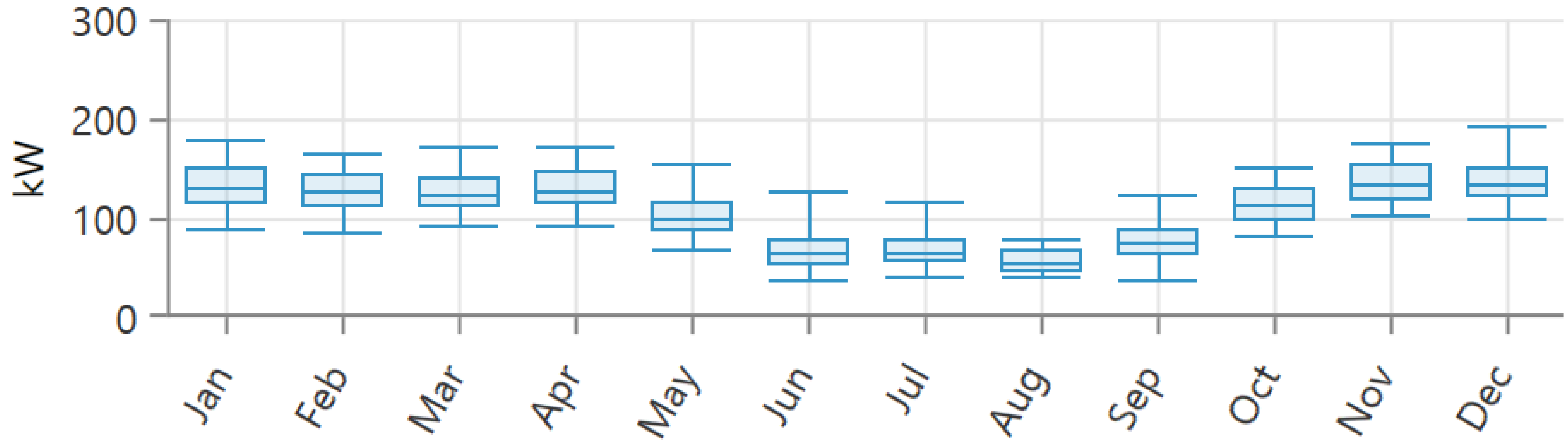




As one might logically expect, the solar resource is summer dominated, whereas the wind and wave resources are winter dominated.

Example Case Study

Given the chosen location, one might also assume a winter dominated (space heating) load on the order of 100 kW average (say, about 2.5 kW per capita) with up to 200 kW peaks.



Example Case Study

Since Spring Island is isolated, the price of diesel (both cost per volume and delivery cost) will strongly influence the cost optimal integration scheme. Fuel prices are quite volatile, however, so one might assume fuel + delivery prices anywhere in the interval

$$[1.50, 2.50]\ \$/L$$

and perform a sensitivity analysis on this basis.

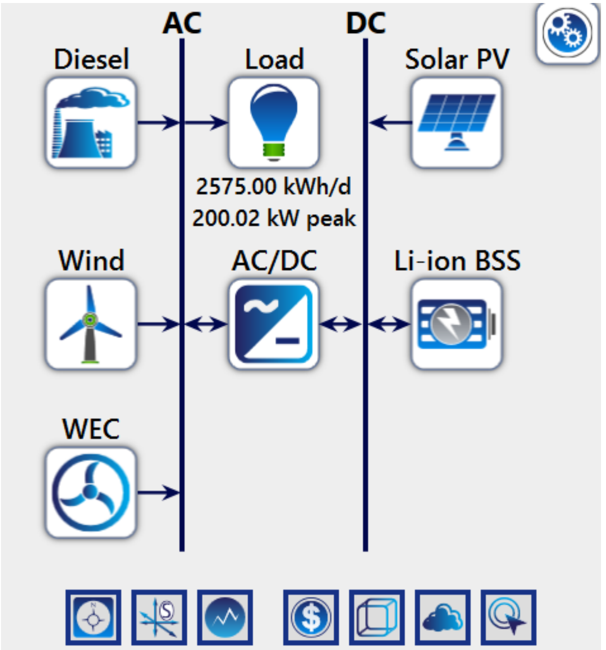
Additionally, the capital, operating, maintenance, and replacement costs of WEC technology is not well known at this time. Therefore, one might assume zero WEC costs and proceed by way of a break-even analysis in comparison to other, better understood technologies.

Spring Island, BC

Example Case Study

A HOMER Pro grid model was constructed for Spring Island which was comprised of a diesel generator, a set of 3 kW wind turbines, a 30 m WEC, an AC/DC converter, a set of 1 kW solar PV panels, and a set of 48 V, 8 kWh Li-ion battery packs. All technology costs were taken to be the HOMER Pro default values.

Finally, the HOMER Pro default economic parameters of 2.00% *p.a.* inflation, 8.00% *p.a.* discount rate, and a 25 year project life were used.



Spring Island grid model

Example Case Study

Results for cost-optimal systems with diesel generation and battery storage

Solar	Wind	Wave	C_{NPV} [$M]	Fuel Use [L/yr]
0	0	0	6.98	268,145
0	0	1	1.33	39,940
0	1	0	7.05	271,890
0	1	1	1.34	39,565
1	*0*	*0*	*6.65*	*231,805*
1	**0**	**1**	**1.27**	**28,590**
1	1	0	7.03	271,740
1	1	1	2.95	98,530

Base case for break-even

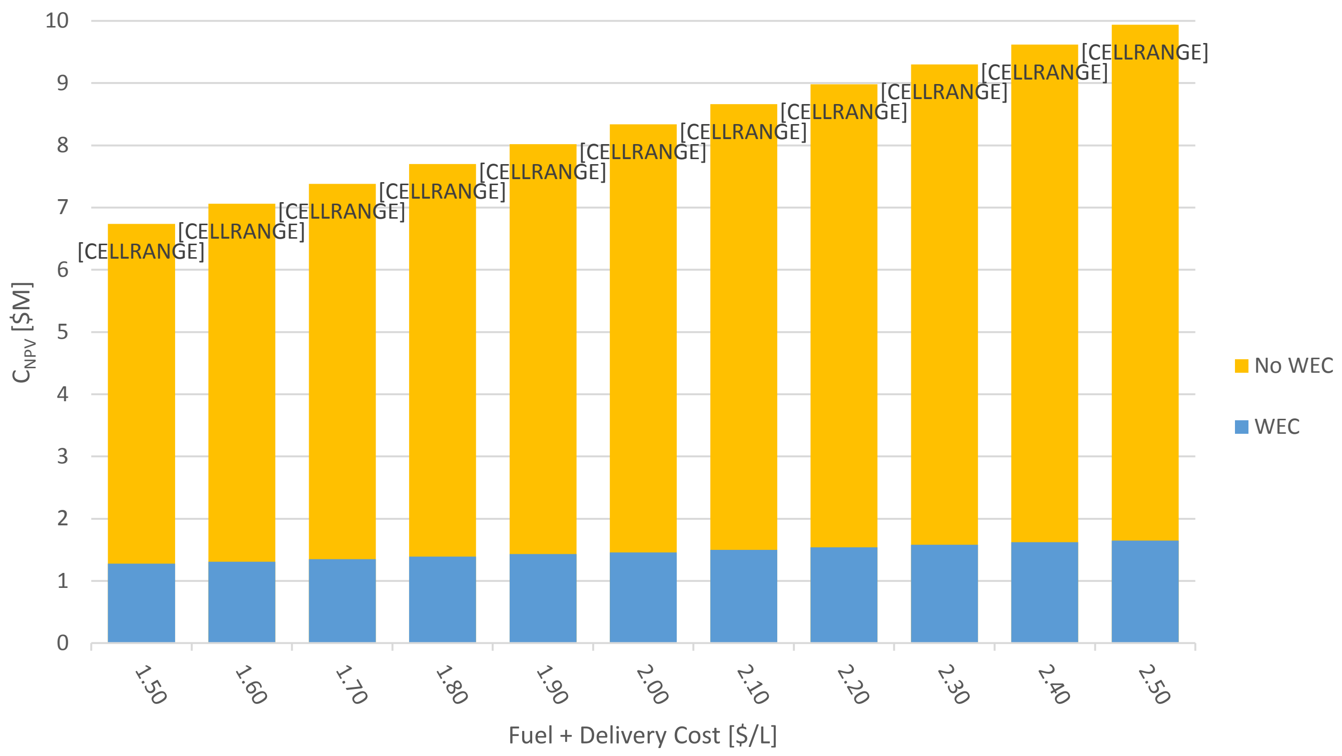
Minimum NPC, diesel consumption

NPC = net present cost

Example Case Study

Diesel-solar base case

Component	Size / Count
Diesel	230 kW
Solar	80 kW
Li-ion Pack (48 V, 8 kWh)	30
AC/DC	140 kW



Break-even analysis, no WEC vs WEC (rel. to diesel-solar base case)

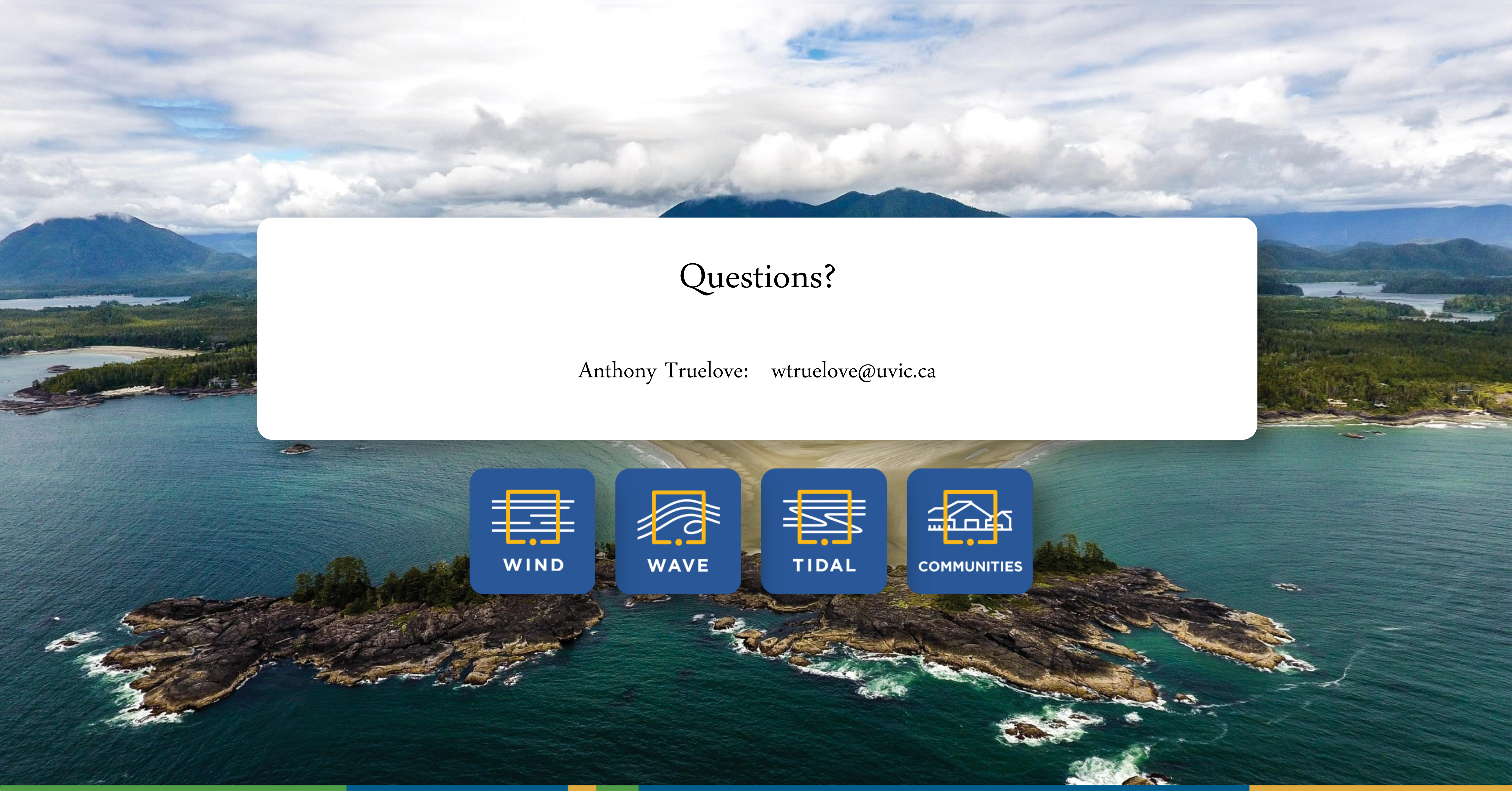
Funding From

Western Economic Diversification Canada

Diversification de l'économie de l'Ouest Canada

Canada

NSERC
CRSNG



Questions?

Anthony Truelove: wtruelove@uvic.ca

WIND

WAVE

TIDAL

COMMUNITIES

Constraints on Variance Density Spectra

Any valid $E(f,\theta)$, or $E(f)D(\theta)$, should exhibit the following properties

$$E(f) \geq 0 \;\text{ and }\; D(\theta) \geq 0$$

$$\text{var}[\eta] = \int_0^{2\pi} \int_0^{\infty} E(f)D(\theta)\, df d\theta$$

$$H_s = 4\sqrt{\text{var}[\eta]}$$

$$T_p = \frac{1}{f_p} \;\text{ where }\; E\left(f_p\right) = \max_f E(f)$$

$$D\left(\theta_p\right) = \max_\theta D(\theta)$$

Together, H_s, T_p, and θ_p give a condensed description of the sea surface at a point and over some time interval.

Energy Period

Another characteristic period is the energy period, T_e, defined by

$$T_e = \frac{1}{\mathrm{var}[\eta]} \int_0^{2\pi} \int_0^{\infty} \frac{E(f)}{f} D(\theta)\, df d\theta$$

Under a Pierson-Moskowitz expression for $E(f)$, it can be shown that

$$T_e = \frac{5^{3/4} \pi T_p}{10\Gamma\left(\frac{3}{4}\right)} \cong 0.85722 T_p$$

Example Variance Density Spectrum

For a fully developed sea, the Pierson-Moskowitz spectrum (non-directional) is a common choice

$$E(f) = \frac{5}{16}\left(\frac{H_s^2}{T_p^4 f^5}\right)\exp\left(-\frac{5}{4}\left(\frac{1}{T_p f}\right)^4\right)$$

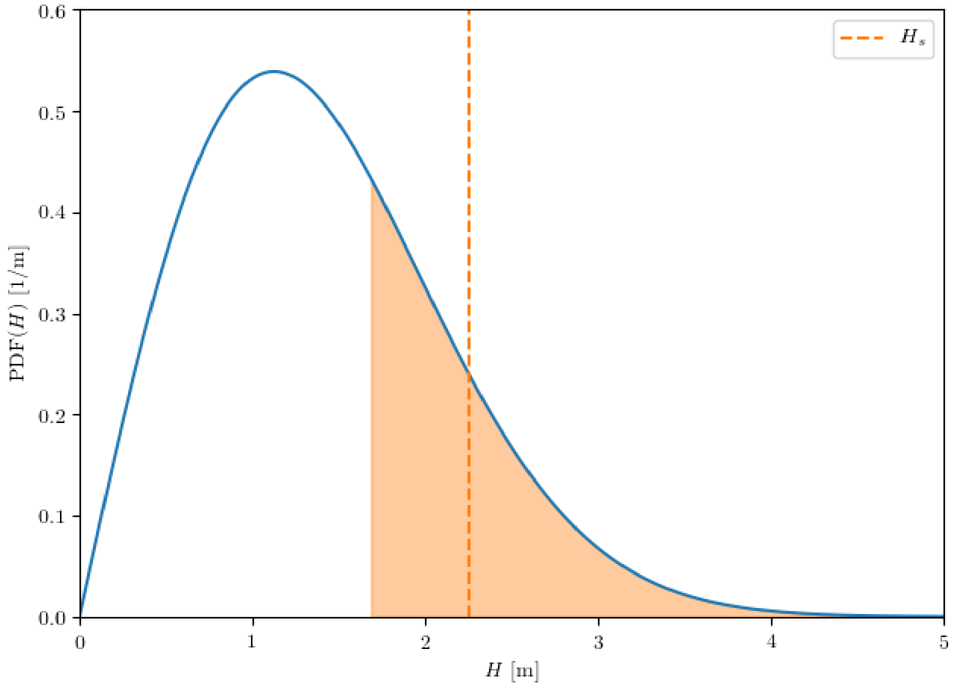
For more dynamic, or developing, seas, the spectrum due to the Joint North Sea Wave Project (JONSWAP) tends to be more representative.

As for the spreading function, one might choose a cosine squared expression, or a Gaussian expression, or any other appropriate expression.

$$D(\theta) = \frac{1}{\pi}\cos^2\left(\frac{\theta-\beta}{2}\right) \qquad D(\theta) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(\theta-\theta_p)^2}{2\sigma^2}\right)$$

Significant Wave Height

Given a probability distribution of wave heights at a given point, the significant wave height, H_s, is the mean height of the highest 1/3rd of waves.



Example wave height probability distribution

Peak and Energy Periods

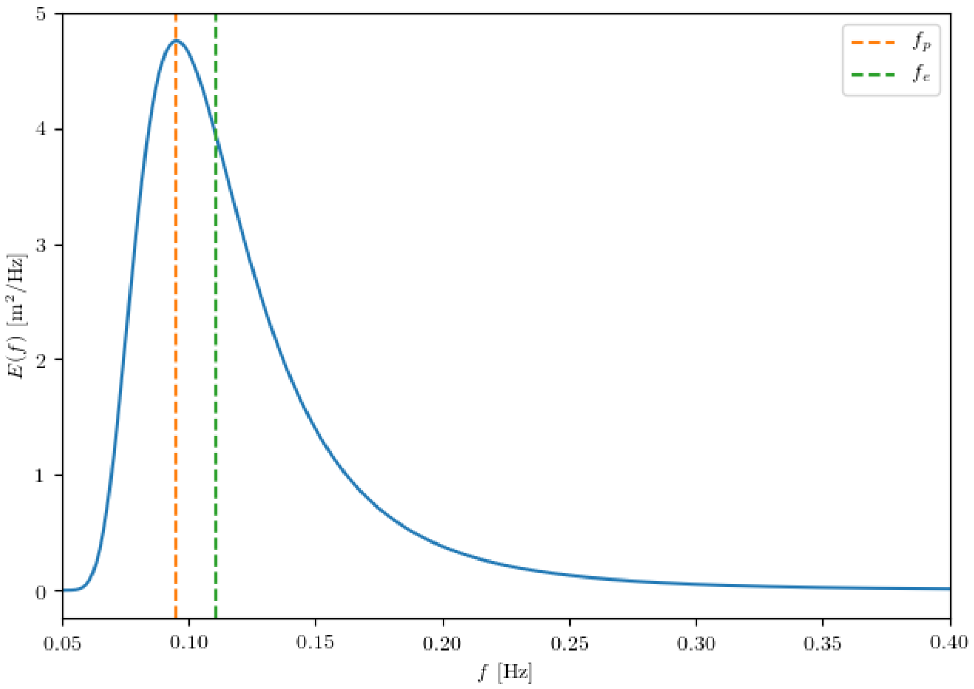
Given a variance density spectrum, the peak period, T_p, is the inverse of the frequency at which the variance density spectrum peaks. The energy period, T_e, is then defined by the moment ratio

$$T_e = \frac{m_{-1}}{m_0}$$

where

$$m_n = \int_0^\infty f^n E(f)\, df$$

As such, energy period gives the energy-weighted average period of the wave modes at a given point.



Example variance density spectrum

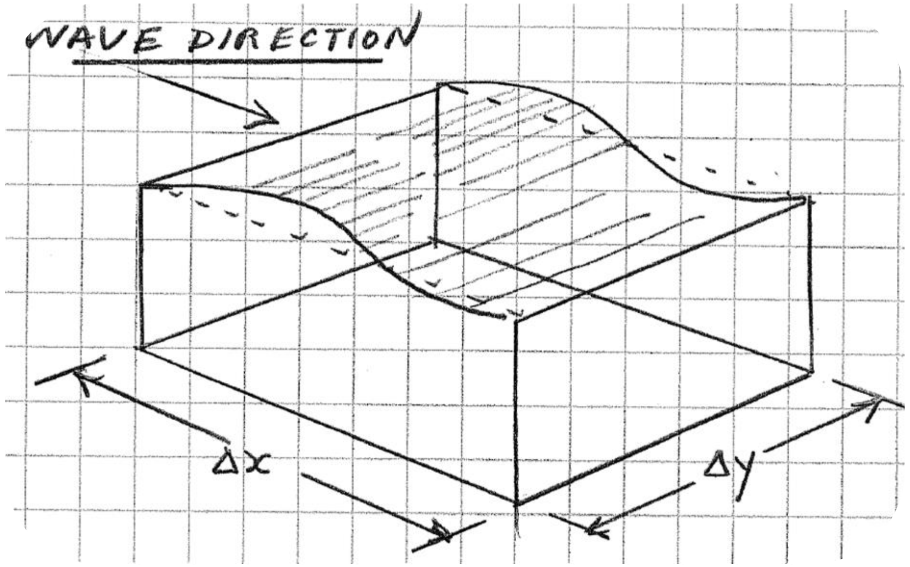
Potential Wave Power Transport in Deep Water Waves

Consider a uni-directional (or nearly so) superposition of planar waves traversing a flat, infinite sea. For a single wave mode propagating over a surface element, the potential wave power transport is

$$J = \frac{P}{\Delta y} = \frac{E}{\Delta t \Delta y} = \frac{\Delta x}{\Delta t}\frac{E}{\Delta x \Delta y} = c_g \frac{E}{\Delta x \Delta y}$$

Taking the group velocity and energy per unit area expressions for deep water waves then yields

$$J = \left(\frac{g}{4\pi f}\right)\left(\frac{\rho g a^2}{4}\right) = \frac{\rho g^2 a^2}{16\pi f}$$



Sea surface element

Potential Wave Power Transport in Deep Water Waves

Therefore, the potential wave power transport from each wave mode is given by

$$J_i = \frac{\rho g^2 a_i^2}{16\pi f_i}$$

Taking a_i to be given by

$$a_i = \sqrt{2E(f_i)(\Delta f)_i}$$

then yields

$$J_i = \frac{\rho g^2 E(f_i)(\Delta f)_i}{8\pi f_i} = \frac{1}{2}\rho g\left(\frac{g}{4\pi f_i}\right)(E(f_i)(\Delta f)_i) = \frac{1}{2}\rho g c_g(f_i)E(f_i)(\Delta f)_i$$

Potential Wave Power Transport in Deep Water Waves

Finally, by letting $\Delta f \to df$ and integrating over all wave modes, the desired result is obtained

$$J = \frac{1}{2}\rho g \int_0^{\infty} c_g(f)E(f)df$$

By a similar argument, this can be extended to directional spectra as well

$$J = \frac{1}{2}\rho g \int_0^{2\pi} \int_0^{\infty} c_g(f,\theta)E(f)D(\theta)\, df d\theta \qquad \blacksquare$$

Variance from Wave Mode Amplitudes

Consider a superposition of planar waves over some time interval $t \in [0, T]$. This may be expressed by

$$\eta(x, y, t) = \sum_{i=1}^{\infty} a_i \cos\left(\frac{2\pi i t}{T} - k_i(x\cos(\theta_i) + y\sin(\theta_i)) + \phi_i\right)$$

By definition, the variance in η is given by

$$\mathrm{var}[\eta] = \mathrm{E}[\eta^2] - \mathrm{E}^2[\eta]$$

Assuming $\mathrm{E}[\eta] = 0$, it follows that

$$\mathrm{var}[\eta] = \frac{1}{T}\int_0^T \left(\sum_{i=1}^{\infty} a_i \cos\left(\frac{2\pi i t}{T} - k_i(x\cos(\theta_i) + y\sin(\theta_i)) + \phi_i\right)\right)^2 dt$$

Variance from Wave Mode Amplitudes

Expanding and re-arranging then leads to[1]

$$
\begin{aligned}
\mathrm{var}[\eta] &= \cdots \\
&= \sum_{i=1}^{\infty}\left(\frac{a_i^2}{T}\int_0^T \cos^2\left(\frac{2\pi i t}{T}+q_i\right)dt\right) \\
&\quad + \sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\left(\frac{(1-\delta_{ij})a_i a_j}{T}\int_0^T \cos\left(\frac{2\pi i t}{T}+q_i\right)\cos\left(\frac{2\pi j t}{T}+q_j\right)dt\right)
\end{aligned}
$$

where $q_i = -k_i(x\cos(\theta_i) + y\sin(\theta_i)) + \phi_i$. However, by way of orthogonality, this immediately collapses to

$$\mathrm{var}[\eta] = \sum_{i=1}^{\infty}\left(\frac{a_i^2}{T}\int_0^T \cos^2\left(\frac{2\pi i t}{T}+q_i\right)dt\right)$$

which then evaluates as

$$\mathrm{var}[\eta] = \sum_{i=1}^{\infty} a_i^2\left(\frac{1}{2}\cos^2(q_i) + \frac{1}{2}\sin^2(q_i)\right) = \frac{1}{2}\sum_{i=1}^{\infty} a_i^2 \qquad \blacksquare$$

1 I'm admittedly glossing over some details here, namely that the Fourier series is Hölder continuous and thus converges uniformly to the sea-surface elevation. This allows for swapping the integral and infinite sum.