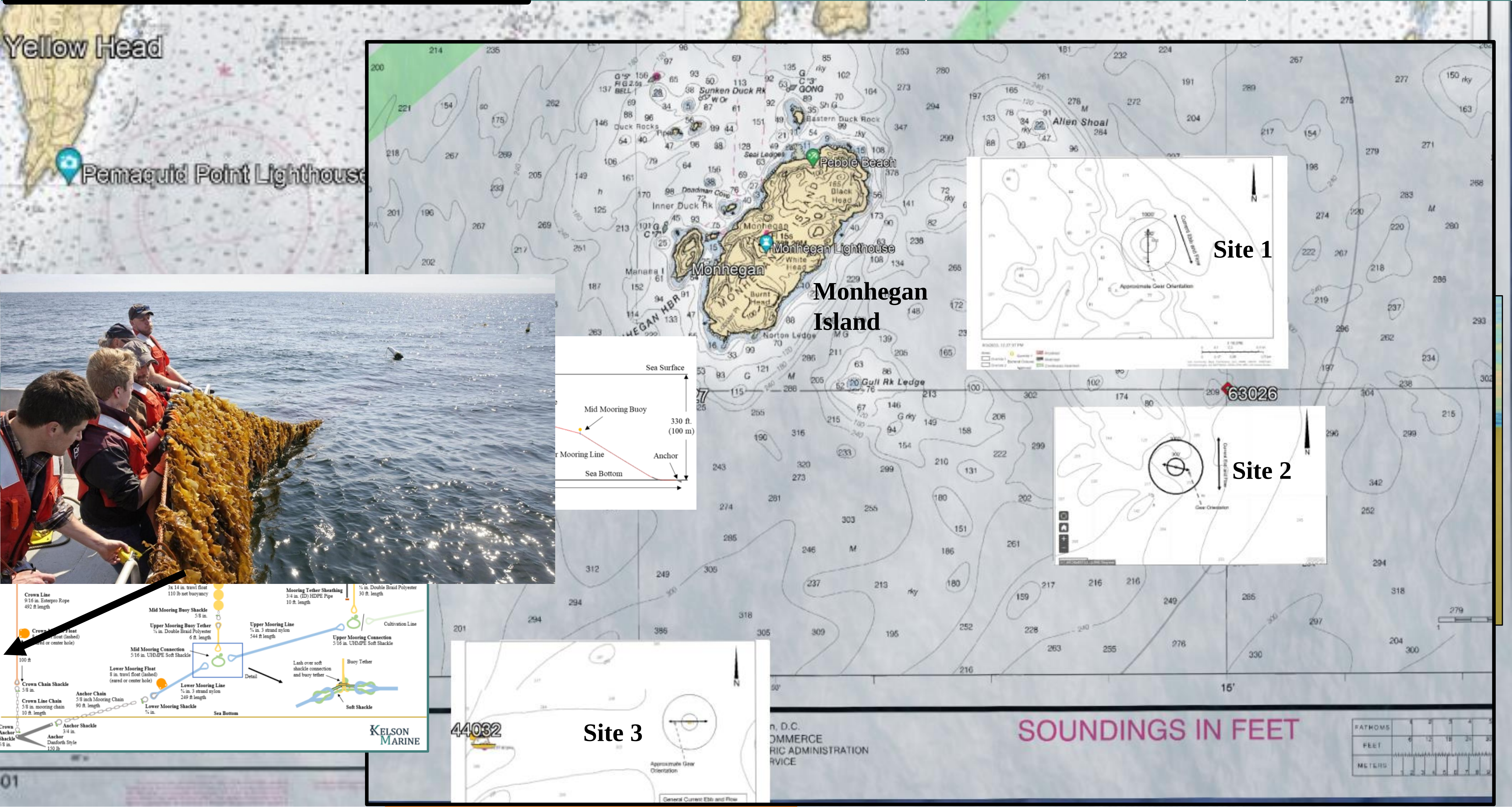
Expansion and Multi-use:
Design and Economics of Co-located Seaweed Farms

Tobias Dewhurst

Kelson Marine Co. 2 Portland Fish Pier Ste. 210, Portland, ME 04101
*Toby@KelsonMarine.com

Kelson Marine


Yellow Head
Pemaquid Point Lighthouse
Monhegan Island
Monhegan Lighthouse
Pebble Beach
Allen Shoal
Duck Rocks
Eastern Duck Rock
Sunken Duck Rk
Inner Duck Rk
Seal Ledges
Manana I
Monhegan
Norton Ledge
Gull Rk Ledge
63026
44032
Site 1
Site 2
Site 3
Approximate Gear Orientation
Gear Orientation
Sea Surface
Mid Mooring Buoy
330 ft.
(100 m)
Mooring Line
Anchor
Sea Bottom
Crown Line
9/16 in. Esterpro Rope
492 ft length
3x 14 in. trawl float
110 lb net buoyancy
Mid Mooring Buoy Shackle
5/8 in.
Upper Mooring Buoy Tether
½ in. Double Braid Polyester
6 ft. length
Mooring Tether Sheathing
3/4 in. (ID) HDPE Pipe
10 ft. length
½ in. Double Braid Polyester
30 ft. length
Upper Mooring Line
¾ in. 3 strand nylon
544 ft length
Cultivation Line
Upper Mooring Connection
5/16 in. UHMPE Soft Shackle
Mid Mooring Connection
5/16 in. UHMPE Soft Shackle
100 ft
Lower Mooring Float
8 in. trawl float (lashed)
(eared or center hole)
Detail
Lash over soft shackle connection and buoy tether
Buoy Tether
Soft Shackle
Crown Chain Shackle
5/8 in.
Crown Line Chain
5/8 in. mooring chain
10 ft. length
Anchor Chain
5/8 inch Mooring Chain
90 ft. length
Lower Mooring Line
¾ in. 3 strand nylon
249 ft length
Lower Mooring Shackle
¾ in.
Anchor Shackle
3/4 in.
Anchor
Danforth Style
150 lb
Crown Anchor Shackle
5/8 in.
KELSON MARINE
SOUNDINGS IN FEET
FATHOMS
FEET
METERS

Resolving “Offshore”: Distance vs. Exposure

Specific factors

Degree of energy

Main site conditions:

- Wave conditions (extreme values and regularity)
- Current conditions (extremne values and regularity)

(1) Sheltered

Effects

- wear on equipment
- operational challenges

Solutions applied

- submersible or larger, more rigid structures
- larger and more specialized vessels

(2) Exposed

Distance from coast

Main site conditions:

- Proximity to infrastructure
- Regulatory regime

(3) Near to land

Effects

- longer transit
- more farming area available
- lower nutrient concentration, less pollution

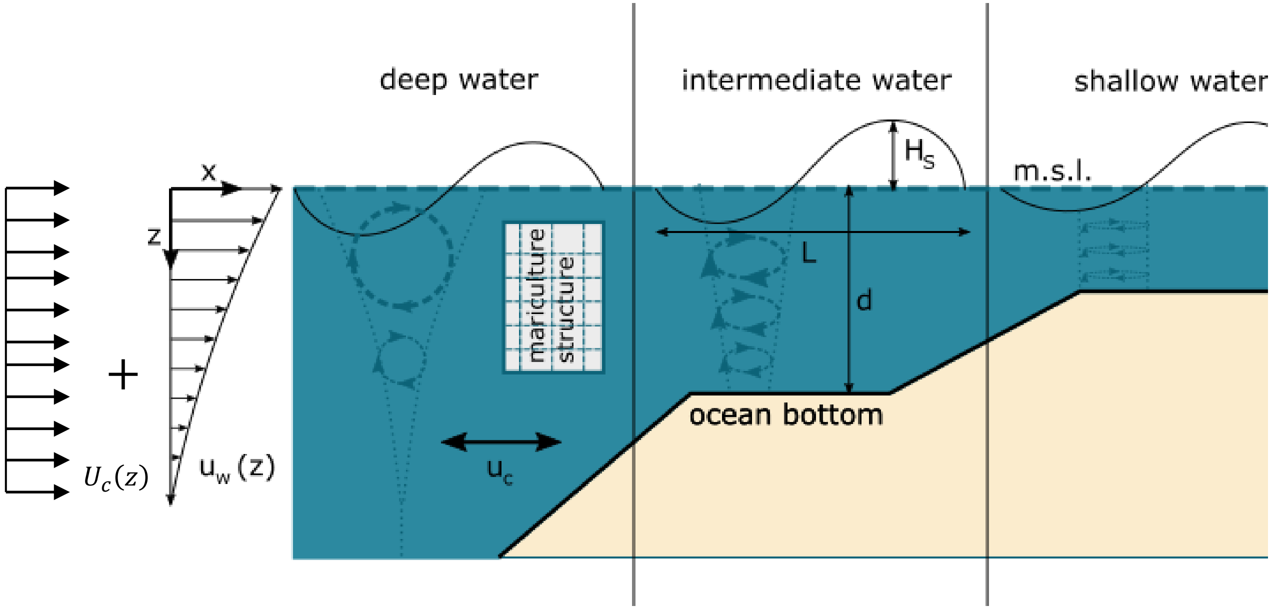
Solutions applied

- automation and remote operations
- longer response times in emergencies

(4) Far from land

Buck, B. H., Bjelland, H., Bockus, A., Chambers, M., Costa-Pierce, B. A., Dewhurst, T., Ferreira, J., Føre, H. M., Fredriksson, D., Goseberg, N., Holmyard, J., Isbert, W., Krause, G., Markus, T., Papandroulakis, N., Sclodnick, T., Silkes, B., Strand, Å., Troell, M., Wieczorek, D., van den Burg, S., Heasman, K. . **Resolving the term ‘offshore aquaculture’ by decoupling ‘exposed’ and ‘distance from shore’ for managers and policy makers.** Journal of the World Aquaculture Society. *In preparation.*

Exposure Index



$$1.\ \mathit{Exposure\ Velocity\ (EV)} = \sqrt{u_w(z)^2 + 2u_w(z)U_c(z) + U_c(z)^2} = U_c(z) + u_w(z)$$

$$2.\ \mathit{Exposure\ Velocity\ at\ Reference\ Depth\ (EVRD)} = U_E = U_{c5} + u_{w5}$$

$$\boxed{3.\ \mathit{Specific\ Exposure\ Energy\ (IEE)} = 1/2\,(U_c(z) + u_w(z))^2}$$

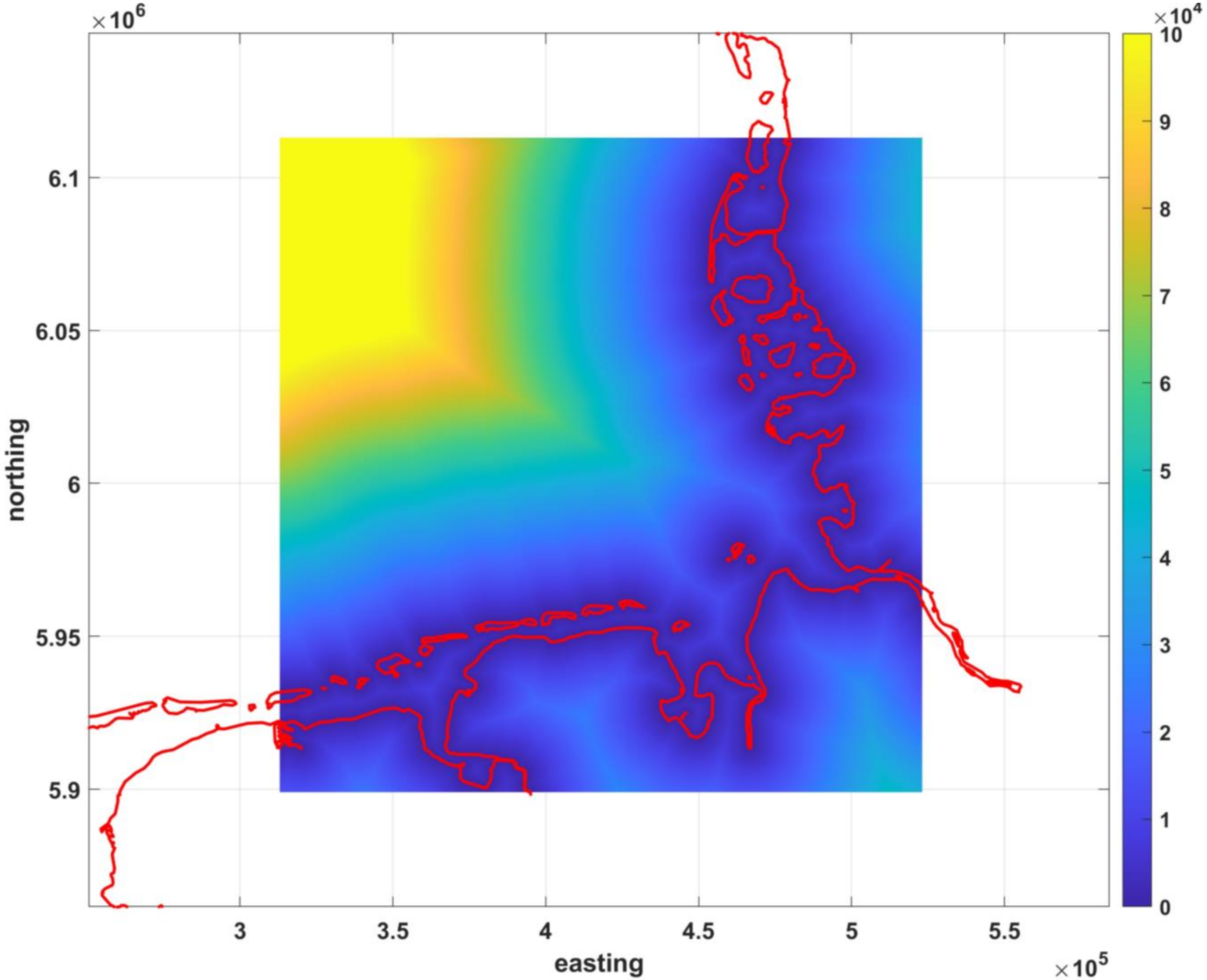
$$4.\ \mathit{Depth-integrated\ Energy\ Flux\ (DEF)} = \frac{\rho g^2 (H_s^2) T_E}{64\pi} + \frac{1}{2}\rho d (U_c)^3$$

$$5.\ \mathit{Structure-centered\ Depth-integrated\ Energy\ (SDE)} = \left(\frac{1}{8}\cdot g \cdot H_s^2 + \frac{1}{2}\cdot d \cdot U^2\right)\cdot \rho \cdot S \cdot A_{structure}$$

$$6.\ \text{Structure} - \text{centered}\ \mathit{Drag-to-buoyancy\ Ratio\ (SDBR)} = \frac{U^2}{2gD}$$

Lojek, O. Goseberg, N., Moe Fore, H., **Dewhurst, T.**, Bölker, T, Heasman, K, Buck, B, Fredriksson, DW, Rickerich, S, A quantified approach to assessing hydrodynamic exposure of mariculture sites. Journal of the World Aquaculture Society. *In preparation.*

Distance from Coast vs. Exposure Energy



Lojek, O. Goseberg, N., Moe Fore, H., **Dewhurst, T.**, Bölker, T, Heasman, K, Buck, B, Fredriksson, DW, Rickerich, S, A quantified approach to assessing hydrodynamic exposure of mariculture sites. Journal of the World Aquaculture Society. *In preparation.*

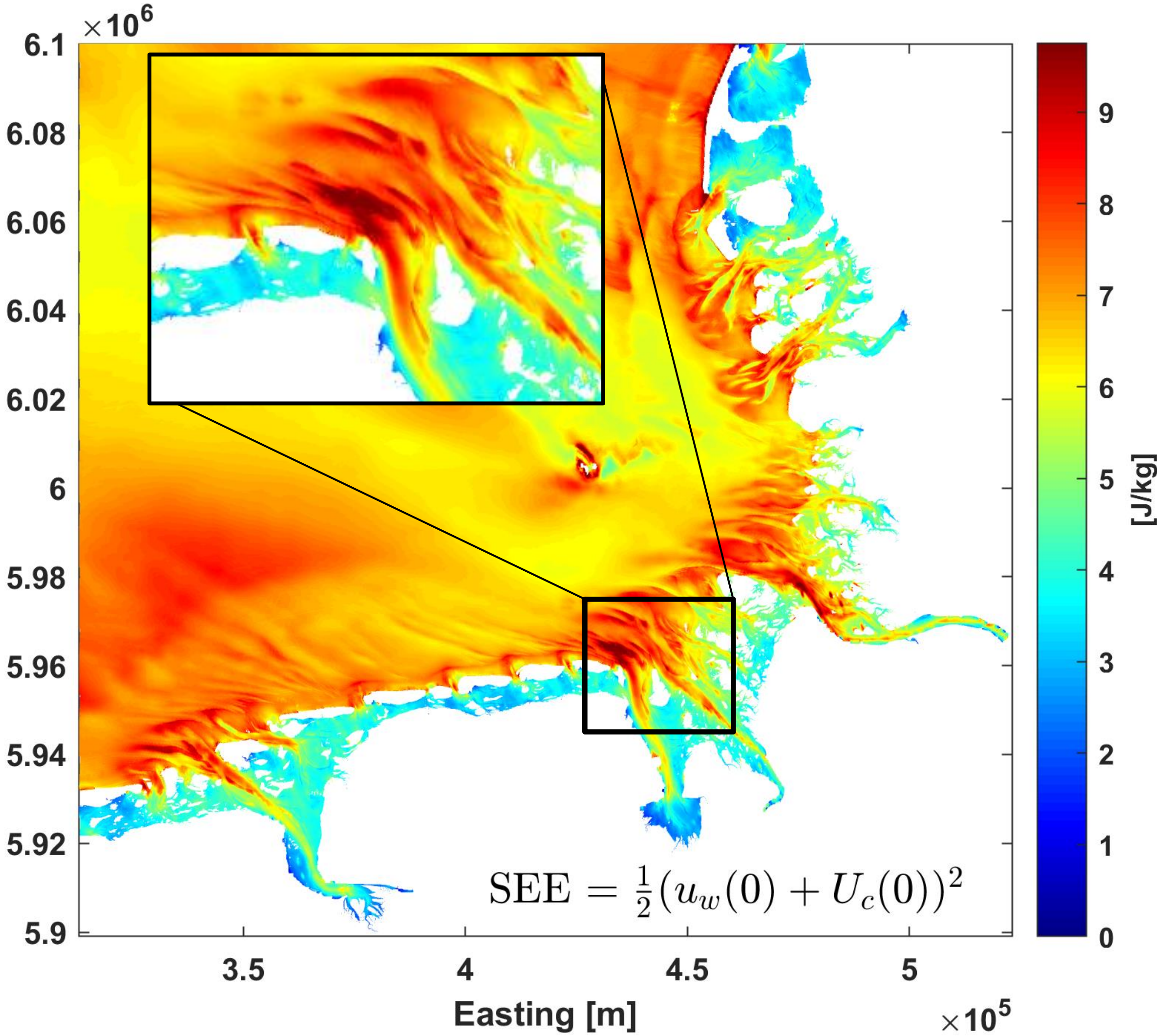
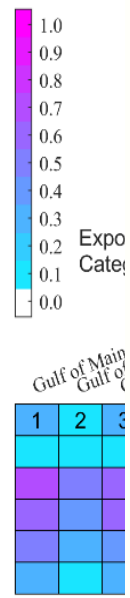
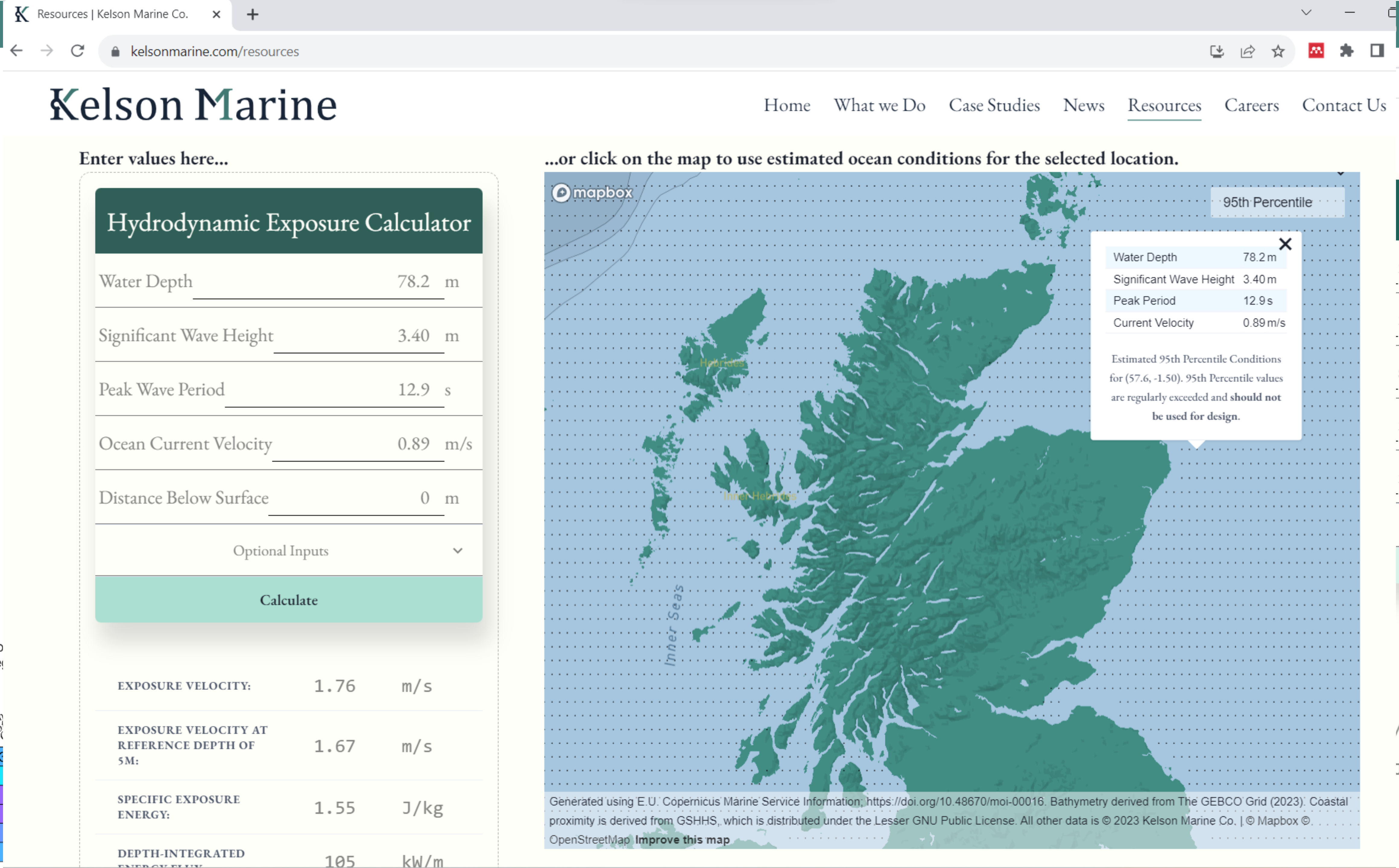


Figure 9: **Specific Exposure Energy** (SEE) for 50-year surface currents and wave induced velocities.





Enter values here...

...or click on the map to use estimated ocean conditions for the selected location.

Hydrodynamic Exposure Calculator

Water Depth	78.2	m
Significant Wave Height	3.40	m
Peak Wave Period	12.9	s
Ocean Current Velocity	0.89	m/s
Distance Below Surface	0	m

Optional Inputs

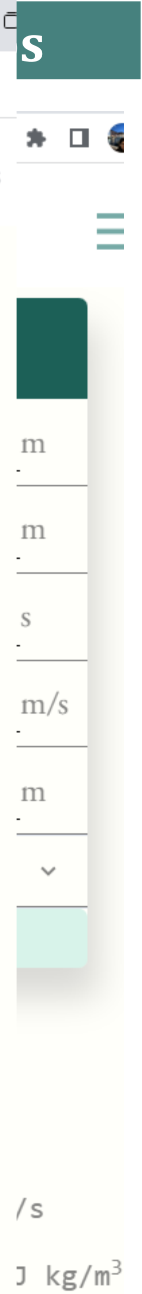
Calculate

EXPOSURE VELOCITY:	1.76	m/s
EXPOSURE VELOCITY AT REFERENCE DEPTH OF 5M:	1.67	m/s
SPECIFIC EXPOSURE ENERGY:	1.55	J/kg
DEPTH-INTEGRATED ENERGY FLUX	105	kW/m

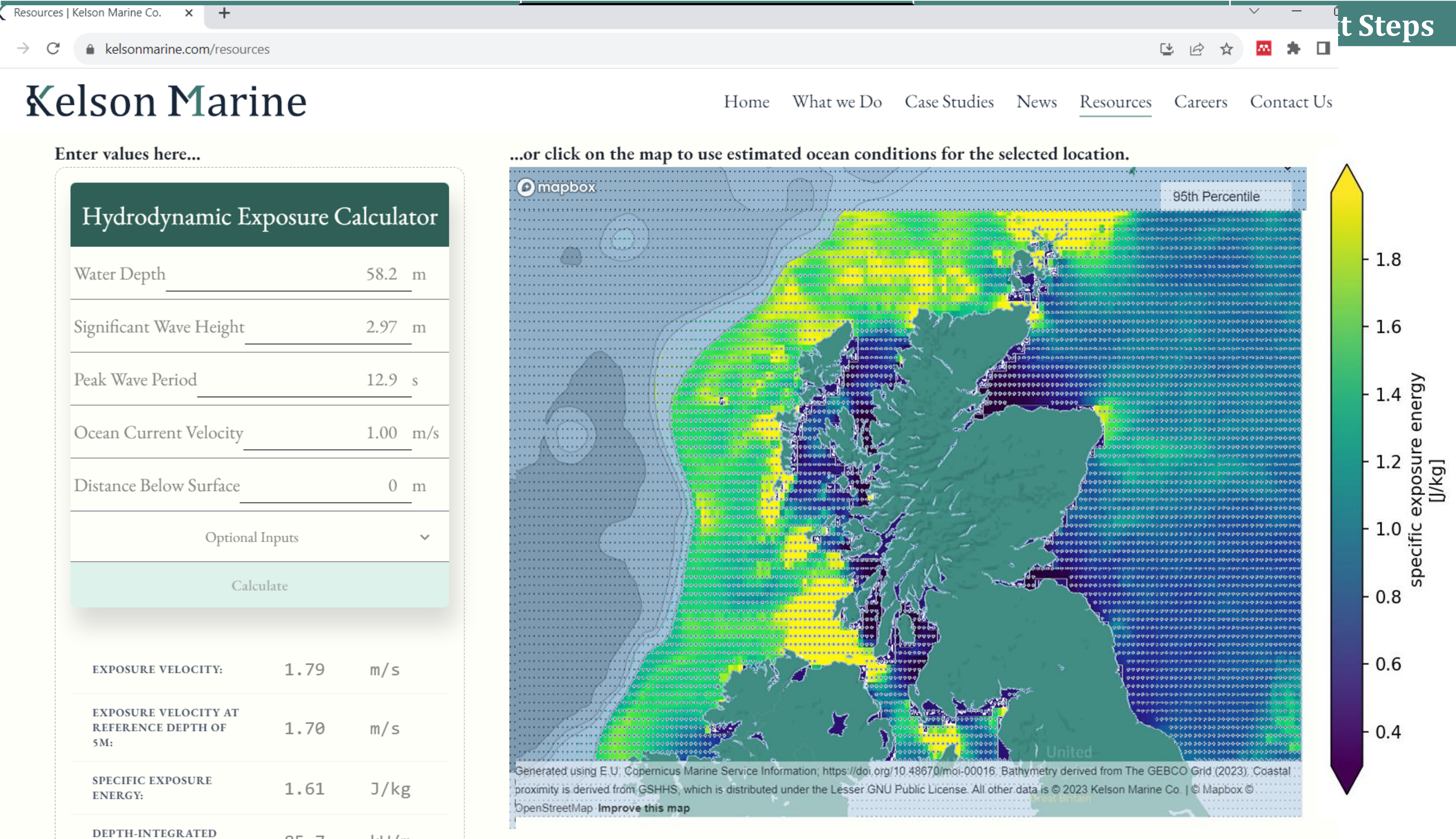
Water Depth	78.2 m
Significant Wave Height	3.40 m
Peak Period	12.9 s
Current Velocity	0.89 m/s

Estimated 95th Percentile Conditions for (57.6, -1.50). 95th Percentile values are regularly exceeded and **should not be used for design.**

Generated using E.U. Copernicus Marine Service Information; https://doi.org/10.48670/moi-00016. Bathymetry derived from The GEBCO Grid (2023). Coastal proximity is derived from GSHHS, which is distributed under the Lesser GNU Public License. All other data is © 2023 Kelson Marine Co. | © Mapbox © OpenStreetMap **Improve this map**



t Steps



Enter values here...

...or click on the map to use estimated ocean conditions for the selected location.

Hydrodynamic Exposure Calculator

Water Depth	58.2	m
Significant Wave Height	2.97	m
Peak Wave Period	12.9	s
Ocean Current Velocity	1.00	m/s
Distance Below Surface	0	m

Optional Inputs

Calculate

EXPOSURE VELOCITY:	1.79	m/s
EXPOSURE VELOCITY AT REFERENCE DEPTH OF 5M:	1.70	m/s
SPECIFIC EXPOSURE ENERGY:	1.61	J/kg
DEPTH-INTEGRATED		

Generated using E.U. Copernicus Marine Service Information; https://doi.org/10.48670/moi-00016. Bathymetry derived from The GEBCO Grid (2023). Coastal proximity is derived from GSHHS, which is distributed under the Lesser GNU Public License. All other data is © 2023 Kelson Marine Co. | © Mapbox © OpenStreetMap **Improve this map**

Saco Bay, Maine:

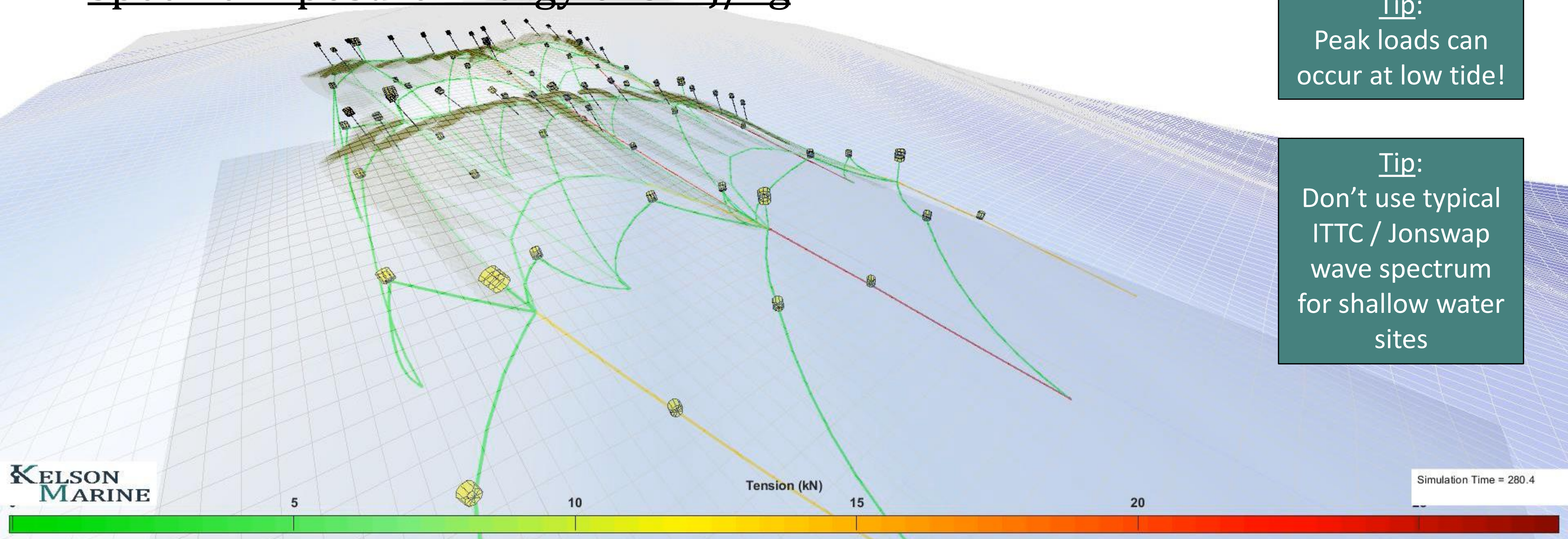
Umaro Foods/UNH/Kelson/UNE/Otherlab/StationKeep/Holdfast

– 0.6 km offshore (2.5 km from mainland)

Saco Bay, Maine:

Umaro Foods/UNH/Kelson/UNE/Otherlab/StationKeep/Holdfast

- 0.6 km offshore (2.5 km from mainland)
- Specific Exposure Energy of 5.1 J/kg



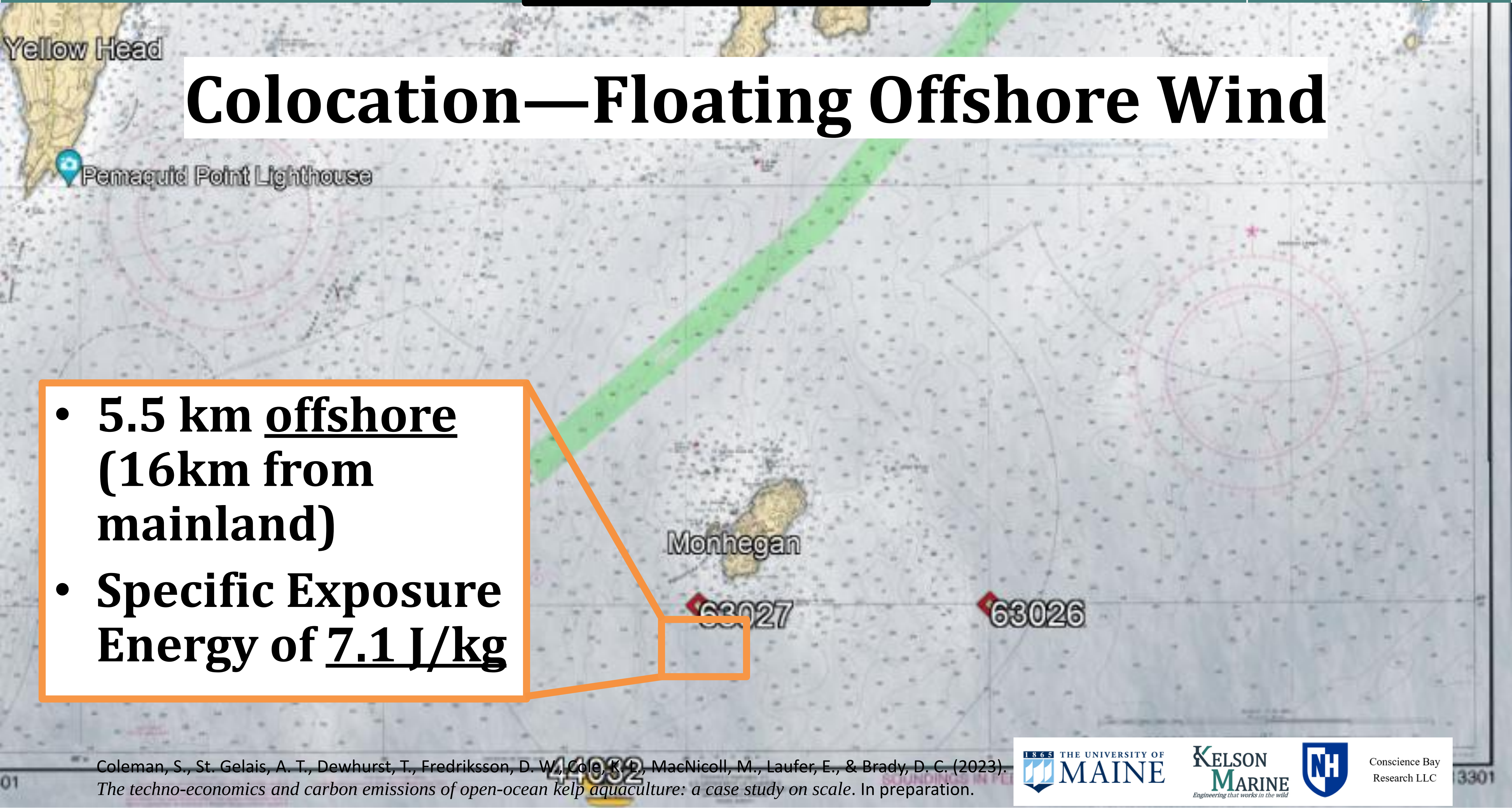
Tip:
Peak loads can occur at low tide!

Tip:
Don’t use typical ITTC / Jonswap wave spectrum for shallow water sites

KELSON MARINE

Sponsored by US DOE ARPA-e MARINER via Trophic LLC and the University of New Hampshire

Colocation—Floating Offshore Wind

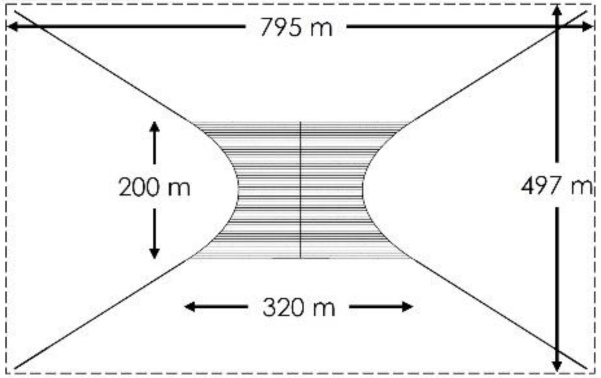


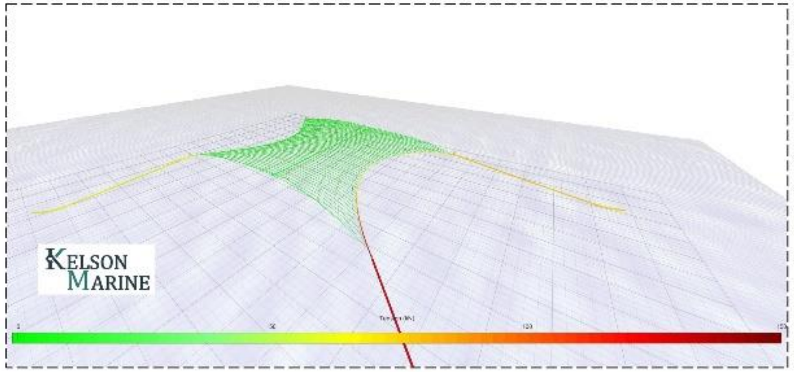
- **5.5 km <u>offshore</u> (16km from mainland)**
- **Specific Exposure Energy of <u>7.1 J/kg</u>**

Coleman, S., St. Gelais, A. T., Dewhurst, T., Fredriksson, D. W., Cole, K. E., MacNicoll, M., Laufer, E., & Brady, D. C. (2023). *The techno-economics and carbon emissions of open-ocean kelp aquaculture: a case study on scale*. In preparation.

Engineering for Co-location

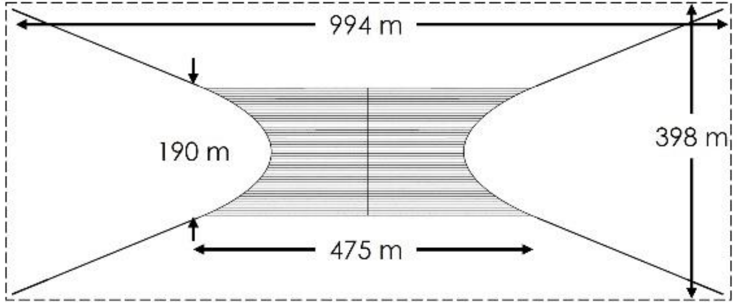
Design A





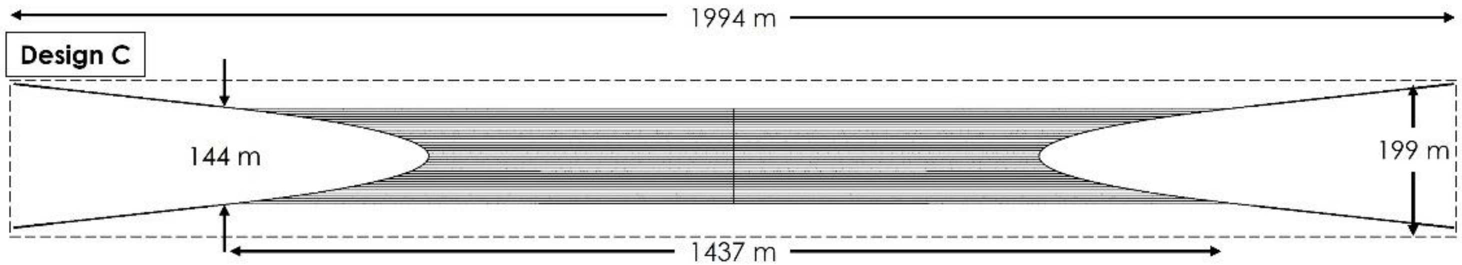
- 3 Aspect Ratios considered
  - All farms have same area
- Design C has most growline
  - Will produce most biomass
  - Will experience highest loading

Design B



Design	Aspect Ratio	Total Grow-Line
A	1.6:1	10.7 km
B	2.5:1	14.7 km
C	10:1	35.9 km

Design C



Coleman, et al. 2022. *“Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal.”* Frontiers in Marine Science.

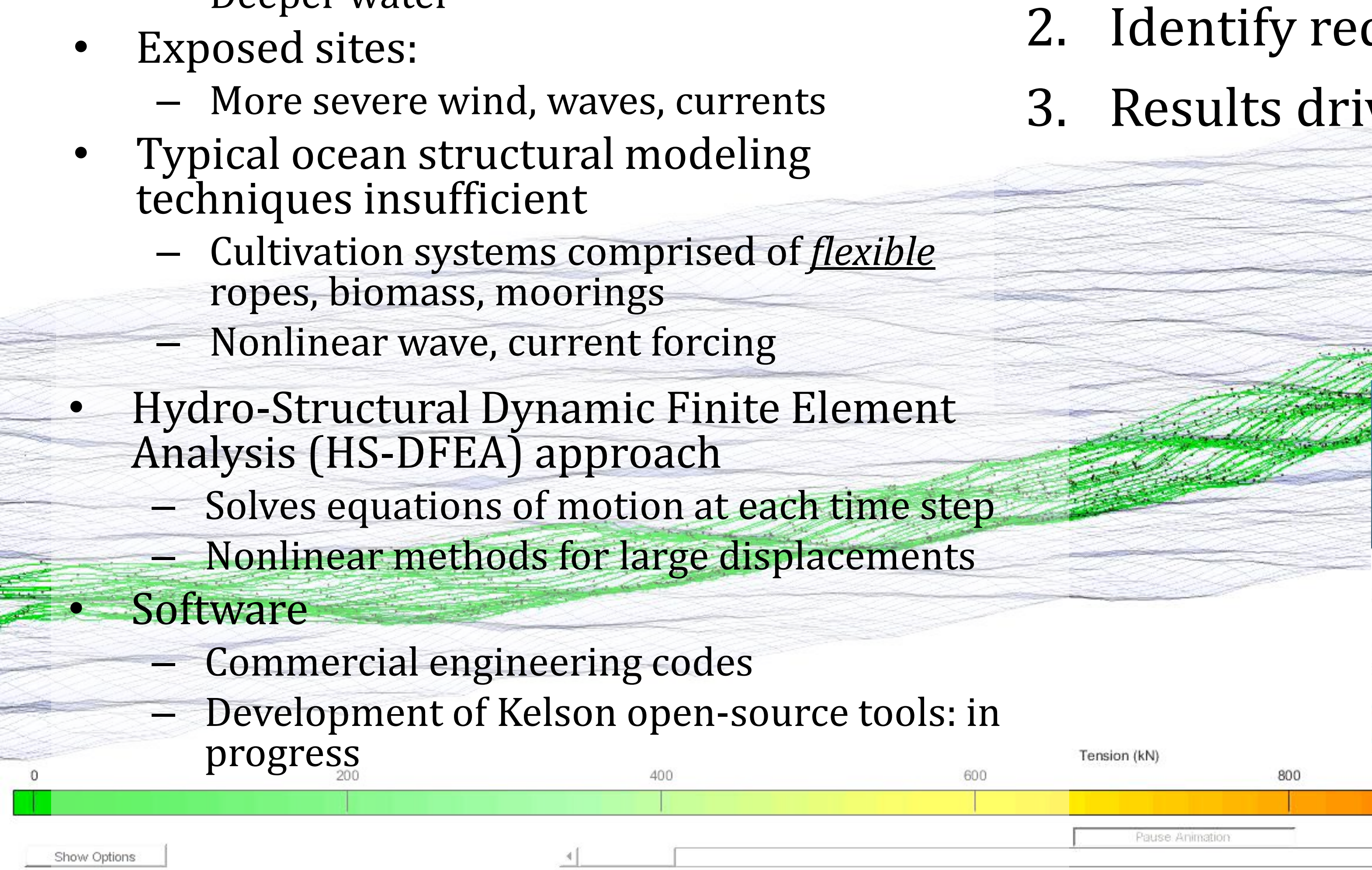
Conscience Bay Research LLC

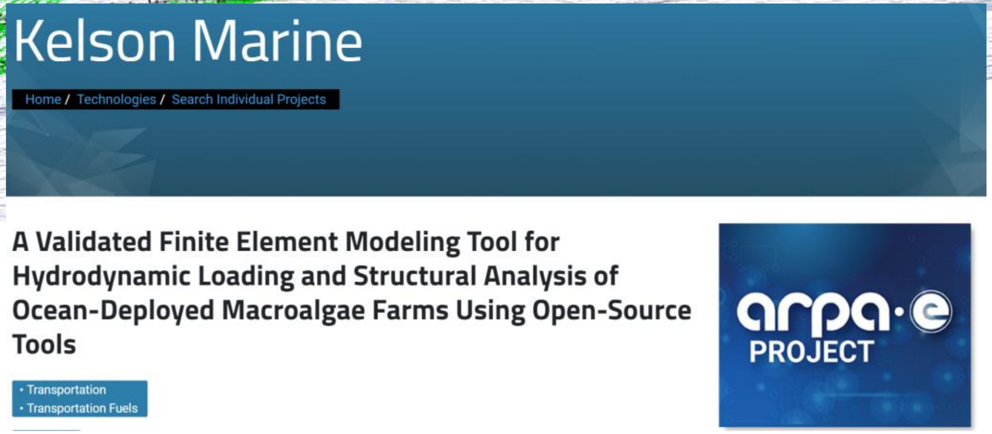
Engineering for Co-location

- Offshore sites:
  - Deeper water
- Exposed sites:
  - More severe wind, waves, currents
- Typical ocean structural modeling techniques insufficient
  - Cultivation systems comprised of *flexible* ropes, biomass, moorings
  - Nonlinear wave, current forcing
- Hydro-Structural Dynamic Finite Element Analysis (HS-DFEA) approach
  - Solves equations of motion at each time step
  - Nonlinear methods for large displacements
- Software
  - Commercial engineering codes
  - Development of Kelson open-source tools: in progress

1. Calculate structural capacities
2. Identify required structural components
3. Results drive techno-economic model

Design A




Kelson Marine

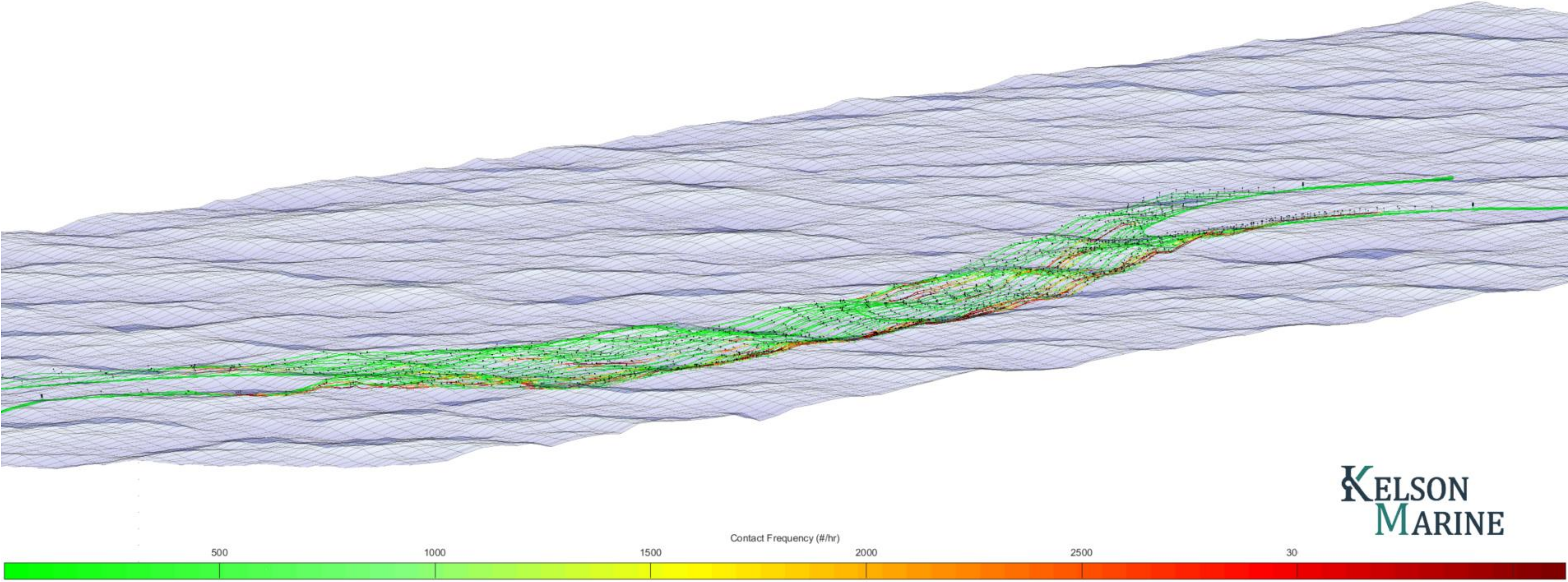
Home / Technologies / Search Individual Projects

A Validated Finite Element Modeling Tool for Hydrodynamic Loading and Structural Analysis of Ocean-Deployed Macroalgae Farms Using Open-Source Tools

- Transportation
- Transportation Fuels

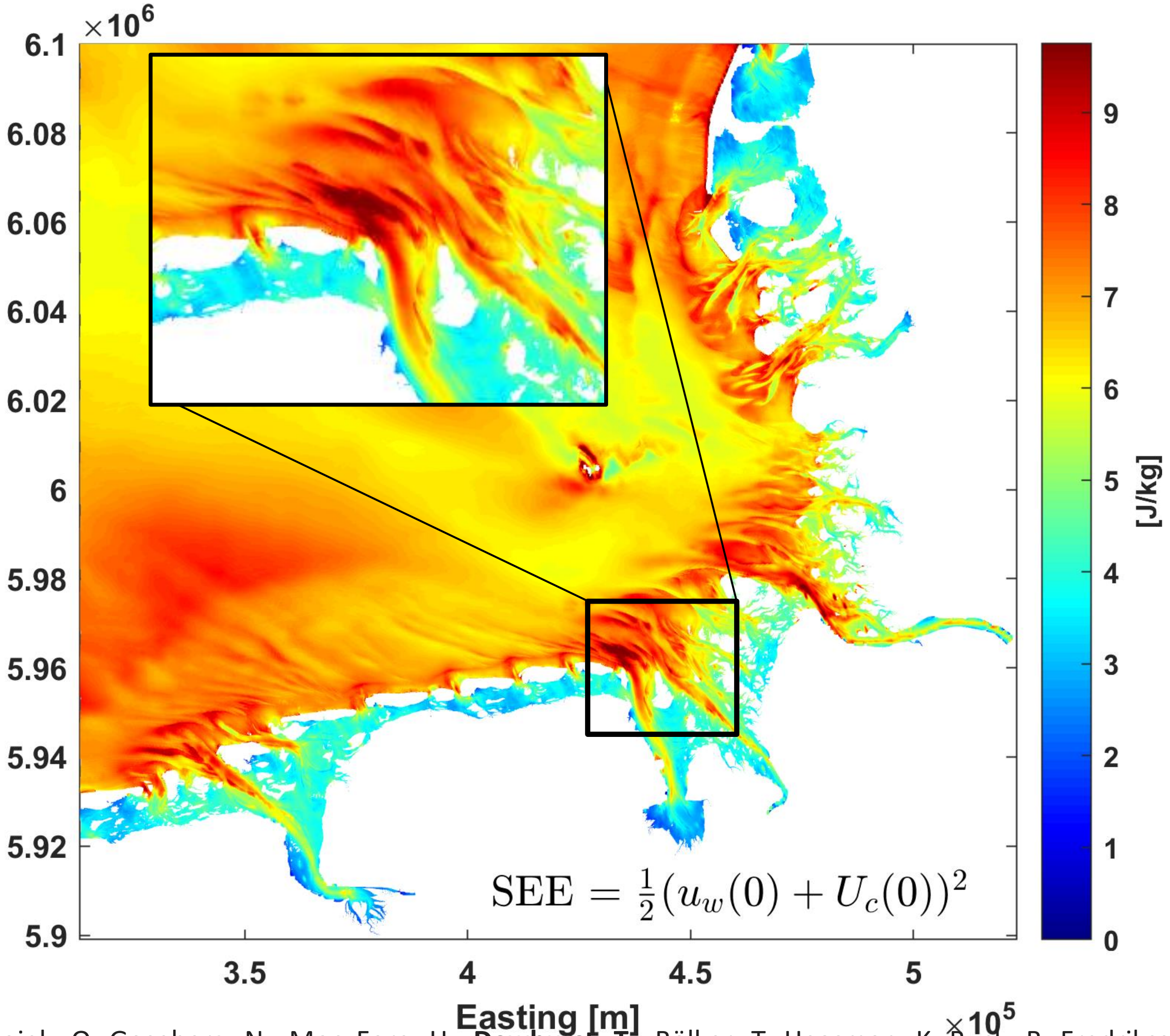
Engineering for Co-location

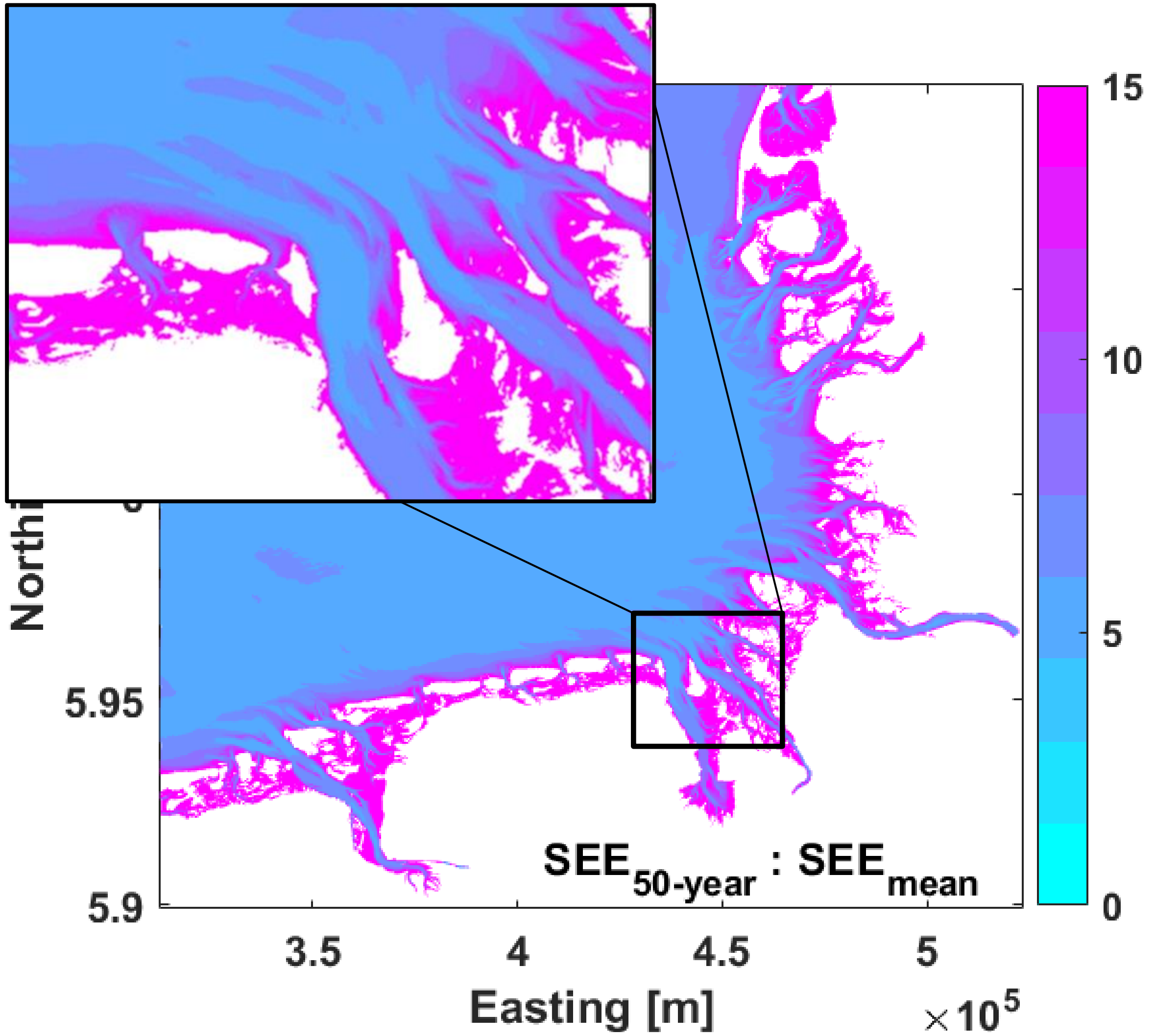
Contact and Tangling



KELSON MARINE

Exposure Energy—"Relative Risk Ratio"



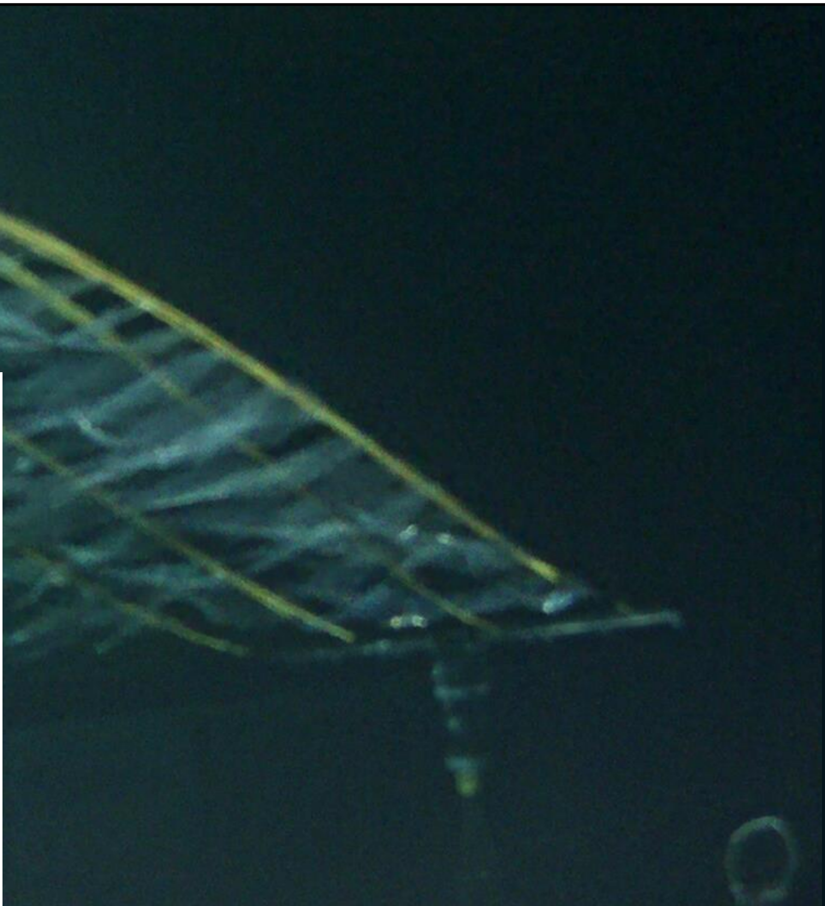


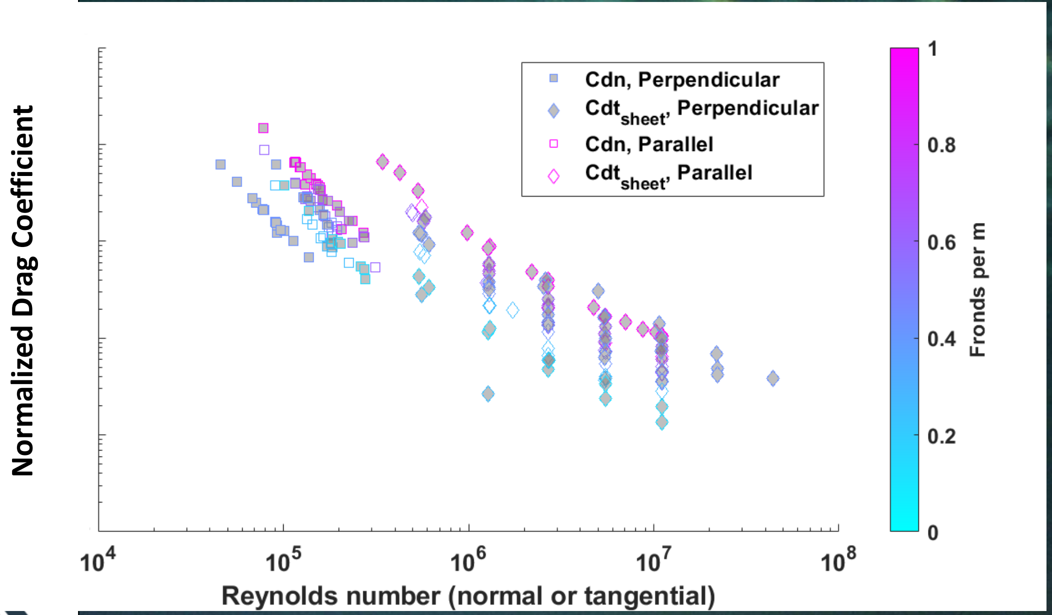
Lojek, O. Goseberg, N., Moe Fore, H., **Dewhurst, T.**, Bölker, T, Heasman, K, Buck, B, Fredriksson, DW, Rickerich, S, A quantified approach to assessing hydrodynamic exposure of mariculture sites. Journal of the World Aquaculture Society. *In preparation.*

Relative Risk Ratio: 50-year Specific Exposure Energy (SEE) divided by Mean Specific Exposure Energy

Macroalgae Hydrodynamics

$$\boldsymbol{f} = \frac{1}{2}\rho D_{\mathbf{n}} C_n |\boldsymbol{V_{Rn}}| \boldsymbol{V}_{\boldsymbol{Rn}}^{\beta_{\mathrm{n}}-1} + \frac{1}{2}\rho D_{\boldsymbol{t}} C_t |\boldsymbol{V}_{\boldsymbol{R}\mathbf{t}}| \boldsymbol{V}_{\boldsymbol{R}\mathbf{t}}^{\beta_{\mathrm{t}}-1} + \rho A \dot{\boldsymbol{V}}_{\boldsymbol{n}} + \rho A C_a \dot{\boldsymbol{V}}_{\boldsymbol{Rn}} .$$





Drag and inertial characteristics of Macrocystis as a function of:

- **Frond length**
- **Fronds per thallus**
- **Thallus spacing (clumps per meter)**
- **Frond tangling**

- **Incident angle (relative to current direction)**
- **Current speed**
- **Wave amplitude and period**

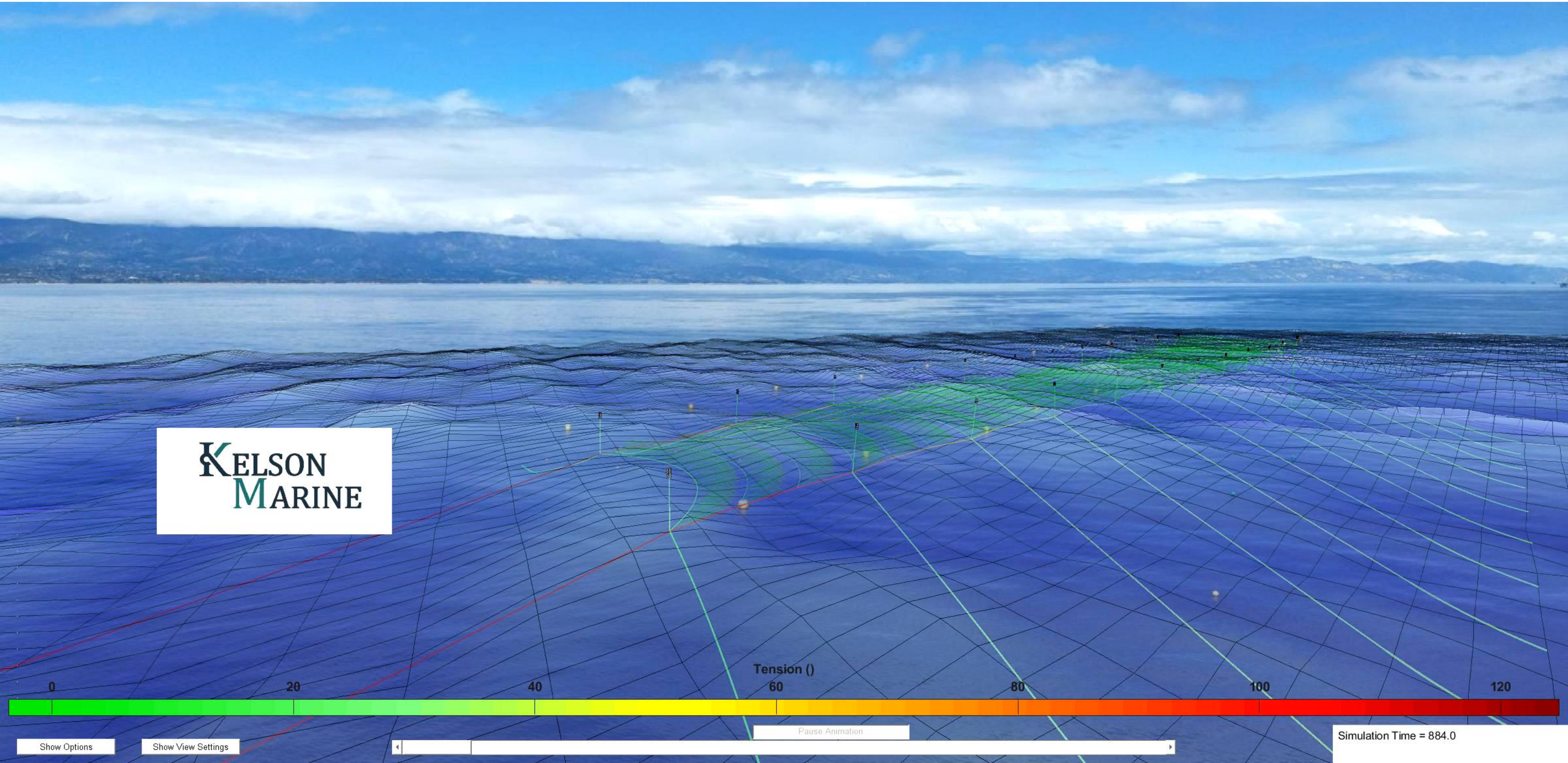
Dewhurst TJ, Dewhurst TB, Fredriksson DW. 2023 Empirically Determined Hydrodynamic Characteristics of Giant Kelp (*Macrocystis Pyrifera).* Journal of Ocean Engineering. *In preparation [Inverted]*

Sponsored by US DOE ARPA-e MARINER via Marine BioEnergy Inc.

Validation—Ocean Rainforest Inc

Photo Credit: Ocean Rainforest. Sponsored by US DOE ARPA-e MARINER

Validation—Ocean Rainforest Inc



Validation—Ocean Rainforest Inc

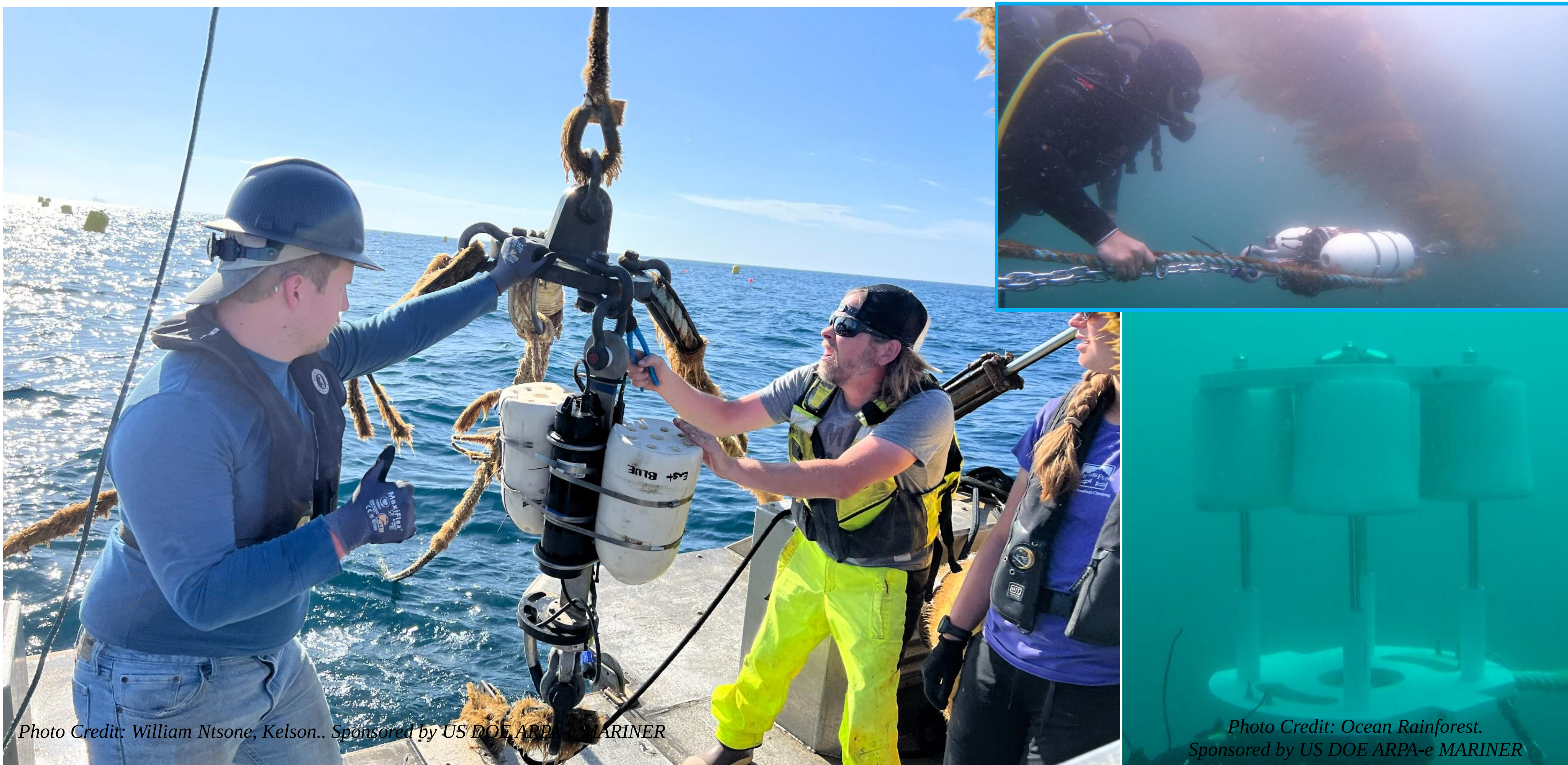
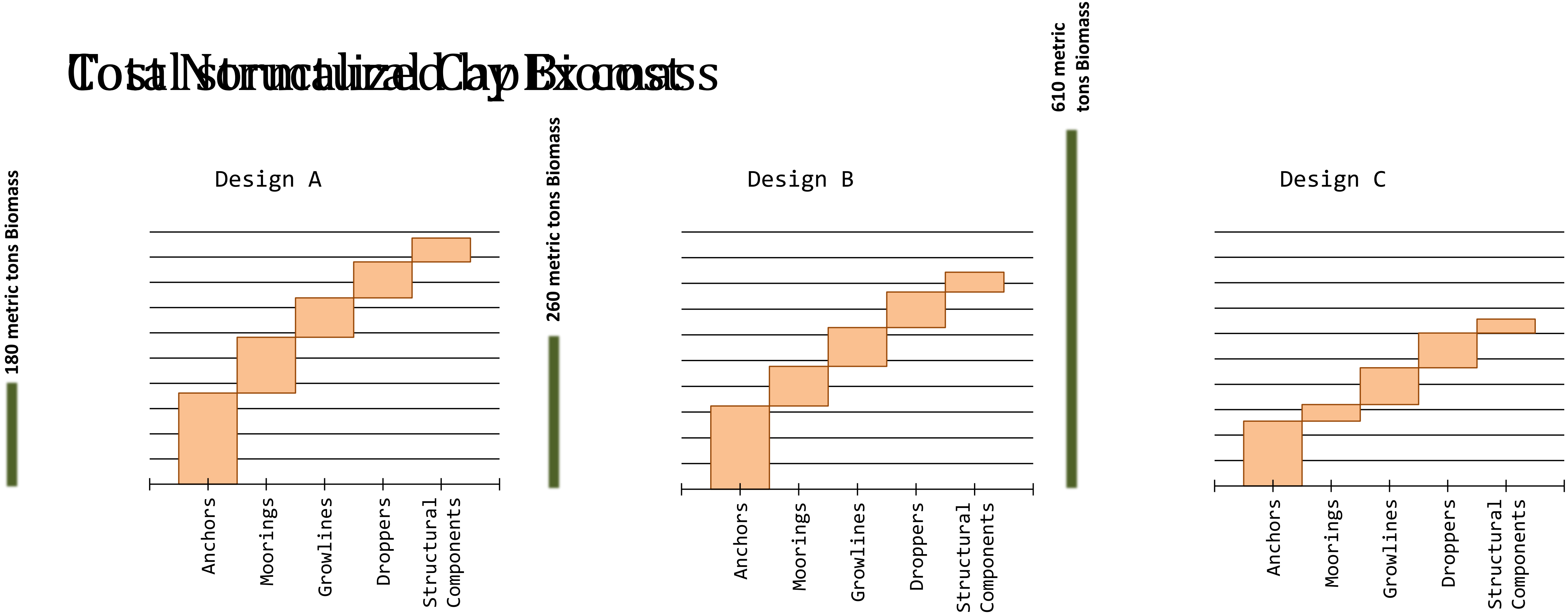


Photo Credit: William Ntsone, Kelson.. Sponsored by US DOE ARPA-e MARINER

Photo Credit: Ocean Rainforest.
Sponsored by US DOE ARPA-e MARINER

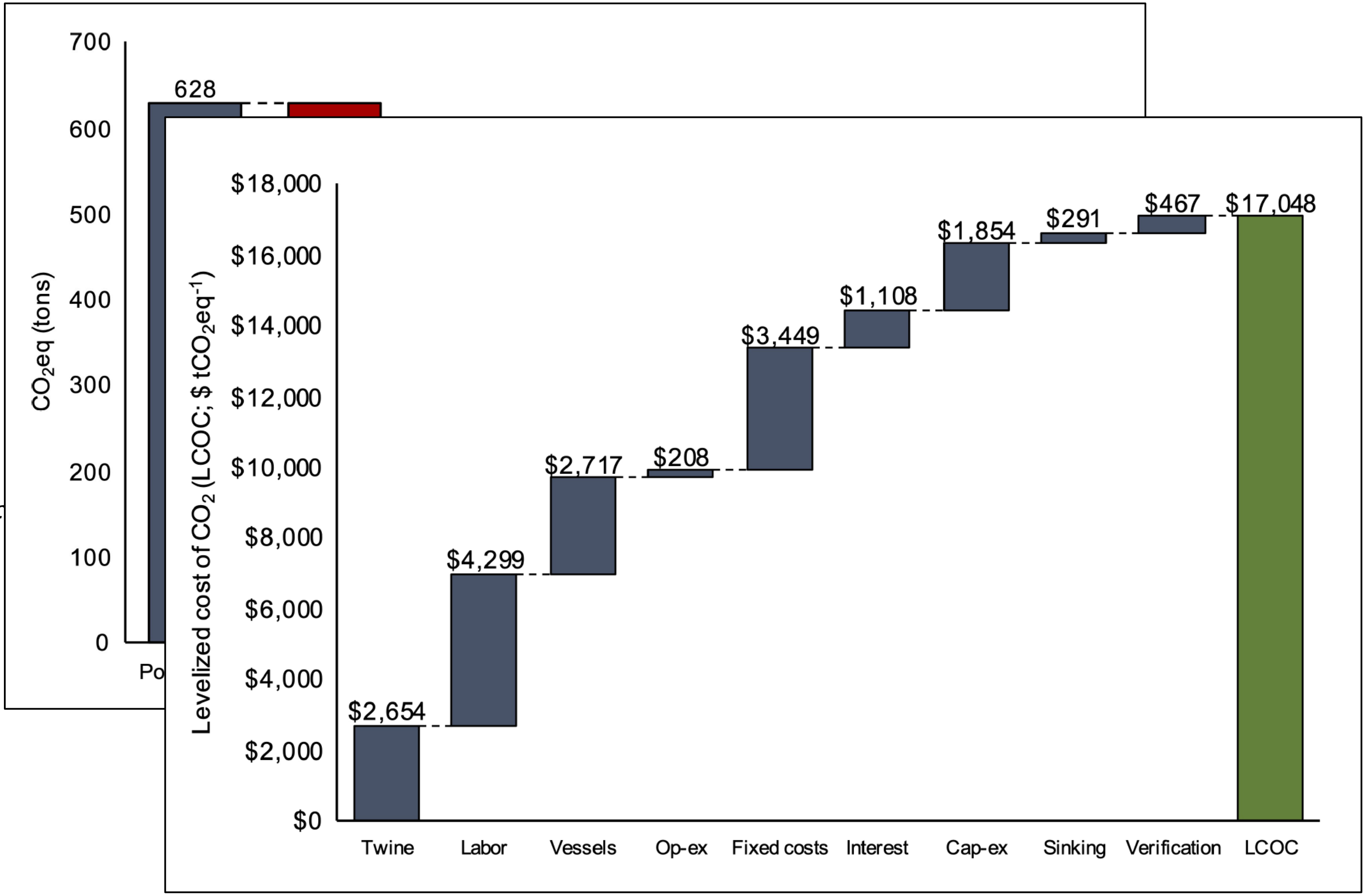
Results: $/kg biomass

Total Normalized Cap Ex
Cost Structure by Biomass



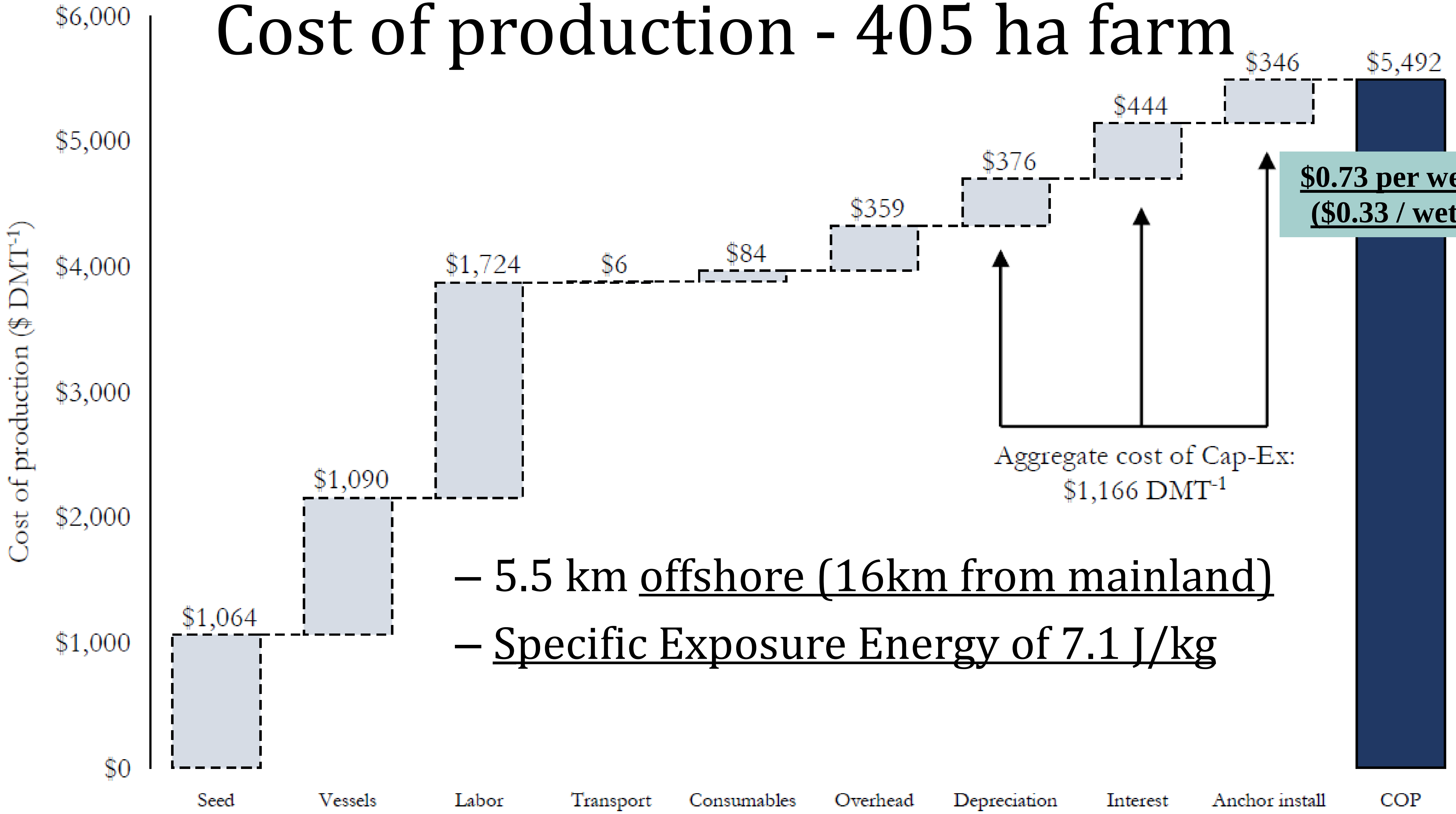
(Kelp CDR Techno-Economics)

- Must account for emissions
  - Net 244 tCO_2eq removed from atmosphere for 628 tCO_2eq sequestered
    - Additionality rate 39%
    - Per 1000-acre farm
- Kelp farming as a means of carbon sequestration <u>using today's farming technologies</u>
  - Would cost near the <u>*upper end of range of CDR technologies*</u>
  - Would require ~20% global GDP to reach Gt-scale
  - Would require farm area ~1.5x the size of U.S. EEZ to reach Gt-scale



Coleman, S., Dewhurst, T., Fredriksson, D. W., St. Gelais, A. T., Cole, K. L., MacNicoll, M., Laufer, E., & Brady, D. C. (2022). *Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal*. Frontiers.

Cost of production - 405 ha farm



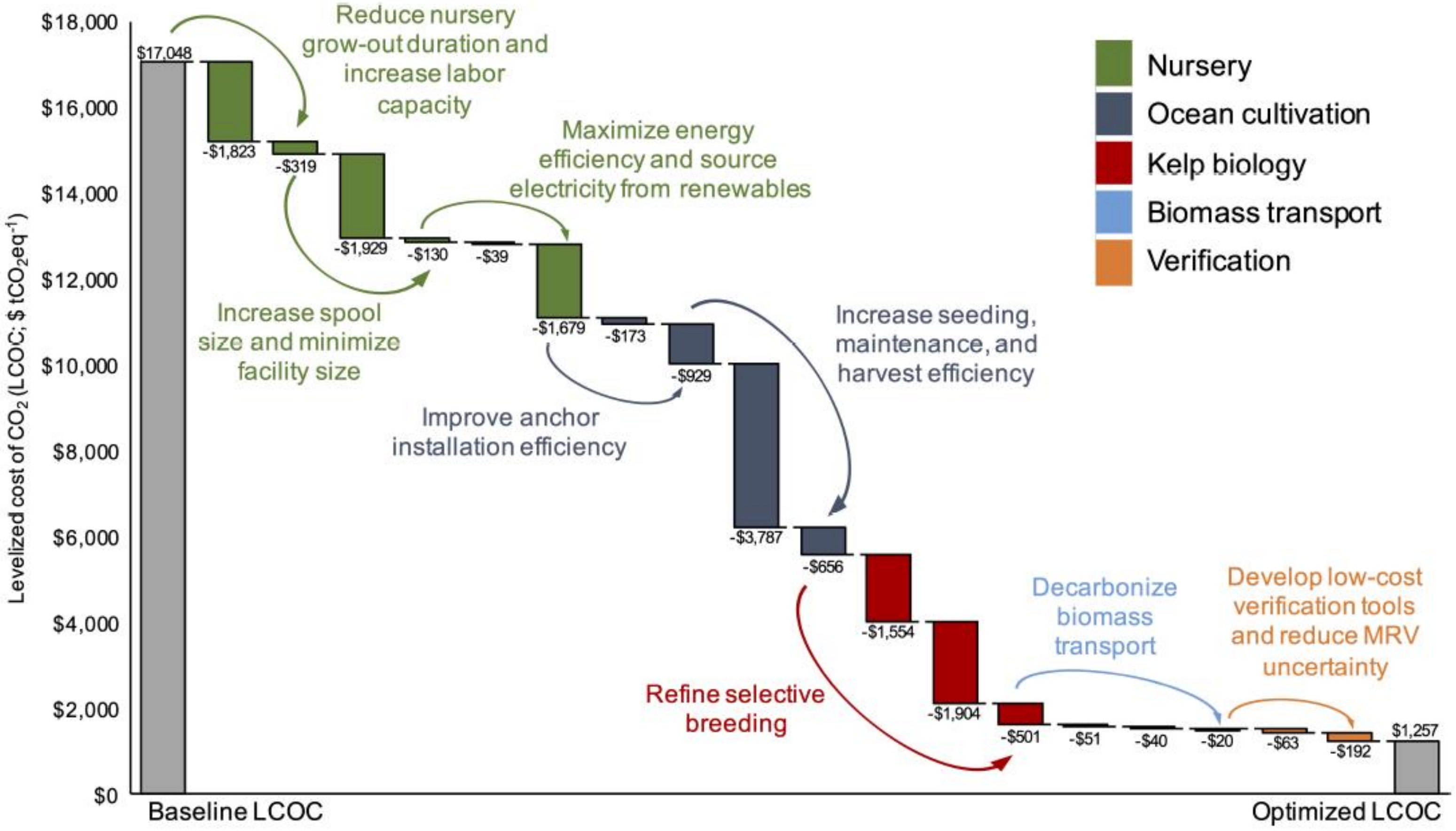
Aggregate cost of Cap-Ex:
$1,166 DMT^{-1}

$0.73 per wet kg
($0.33 / wet lb)

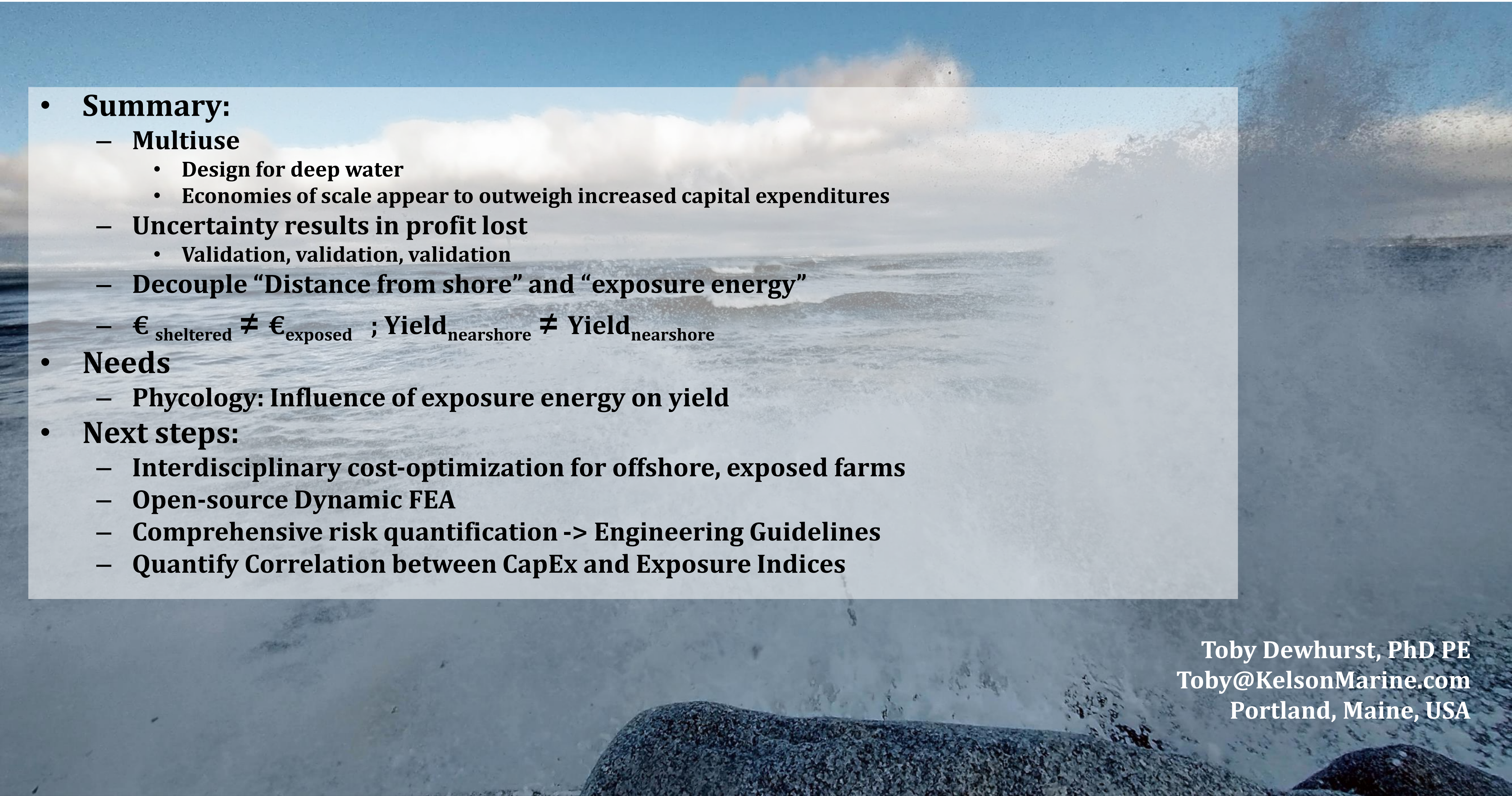
- 5.5 km offshore (16km from mainland)
- Specific Exposure Energy of 7.1 J/kg

$/kg: Continuing Work

- Optimization Targets
  - De-risk farm designs and reduce CapEx
  - Automate seeding, harvest
  - Increase yields through selective breeding
  - Assess cost-benefit of gametophyte nursery culture
  - Decarbonize equipment supply chains and ocean cultivation
  - (Develop low-cost, accurate MRV technologies)



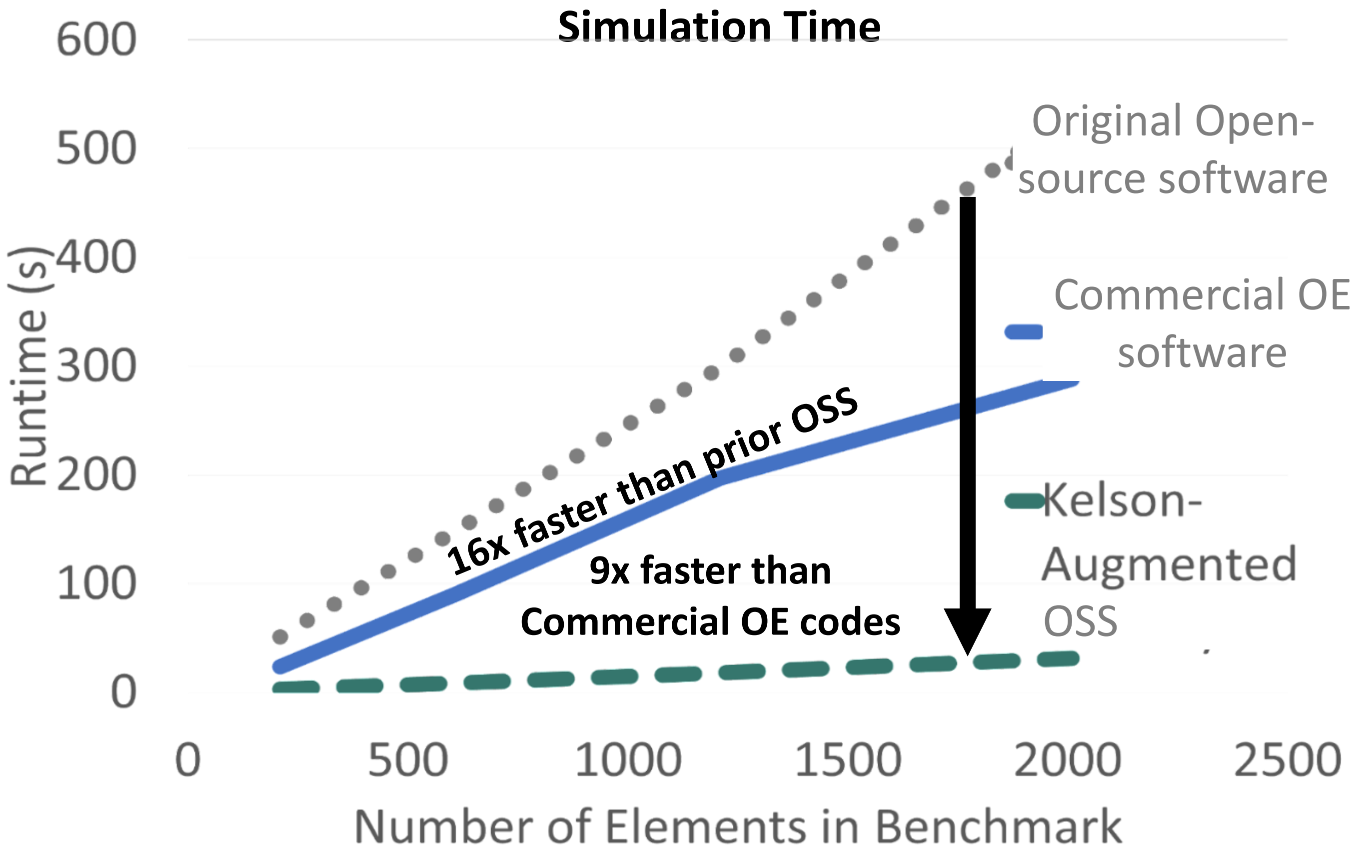
Coleman, S., Dewhurst, T., Fredriksson, D. W., St. Gelais, A. T., Cole, K. L., MacNicoll, M., Laufer, E., & Brady, D. C. (2022). *Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal*. Frontiers.



- **Summary:**
  - **Multiuse**
    - **Design for deep water**
    - **Economies of scale appear to outweigh increased capital expenditures**
  - **Uncertainty results in profit lost**
    - **Validation, validation, validation**
  - **Decouple "Distance from shore" and "exposure energy"**
  - $\text{€}_{\text{sheltered}} \neq \text{€}_{\text{exposed}}$; $\text{Yield}_{\text{nearshore}} \neq \text{Yield}_{\text{nearshore}}$
- **Needs**
  - **Phycology: Influence of exposure energy on yield**
- **Next steps:**
  - **Interdisciplinary cost-optimization for offshore, exposed farms**
  - **Open-source Dynamic FEA**
  - **Comprehensive risk quantification -> Engineering Guidelines**
  - **Quantify Correlation between CapEx and Exposure Indices**

Toby Dewhurst, PhD PE
Toby@KelsonMarine.com
Portland, Maine, USA

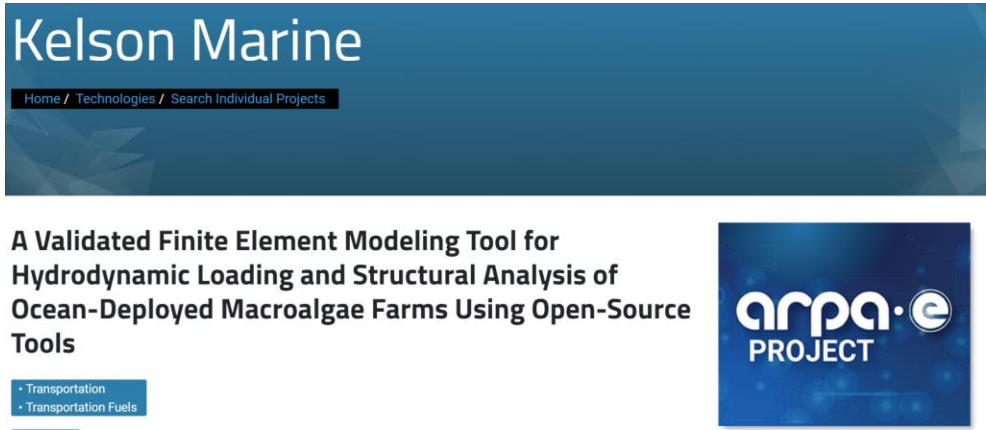
Hydro-/Structural Dynamic FEA in Open-source Tools



16x faster than prior OSS

9x faster than Commercial OE codes

- Advanced Features
  - <u>Non-quadratic drag equations</u>
  - 4-dimensional current variation (wakes)
  - Realistic mixed directional seas
  - Variable seafloor depth
  - Kinematic stretching
  - …


Kelson Marine

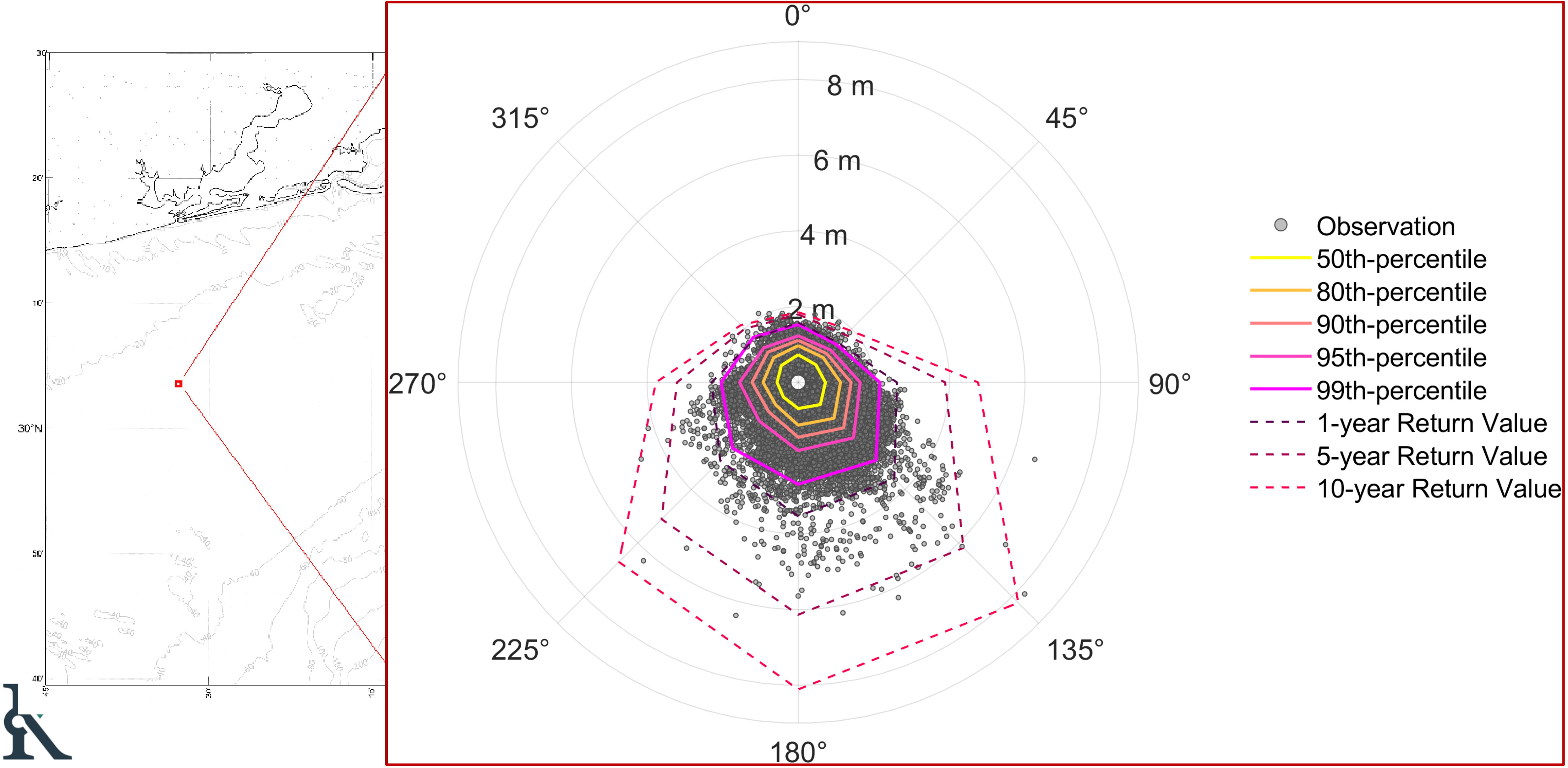
Home / Technologies / Search Individual Projects

A Validated Finite Element Modeling Tool for Hydrodynamic Loading and Structural Analysis of Ocean-Deployed Macroalgae Farms Using Open-Source Tools

- Transportation
- Transportation Fuels

arpa·e PROJECT

Metocean Risk Analysis

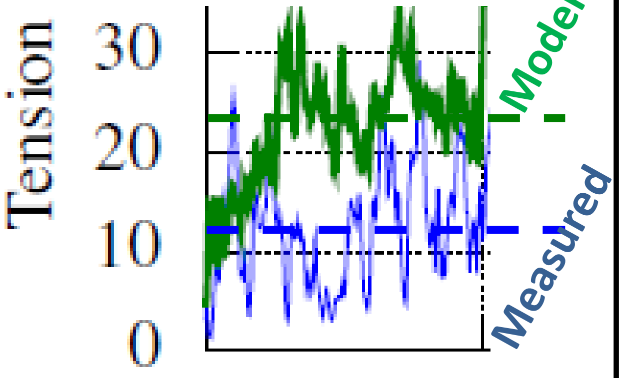


Numerical Modeling—A brief history

Dewhurst (2016). Observed and predicted mooring line tensions for the submerged mussel raft

	Mean Tension, N	Standard deviation, N
	Line 2	Line 2
Field Experiment	1450	38
OrcaFlex	1920	84

Nicoll et al., 2011 (Fish Cage)



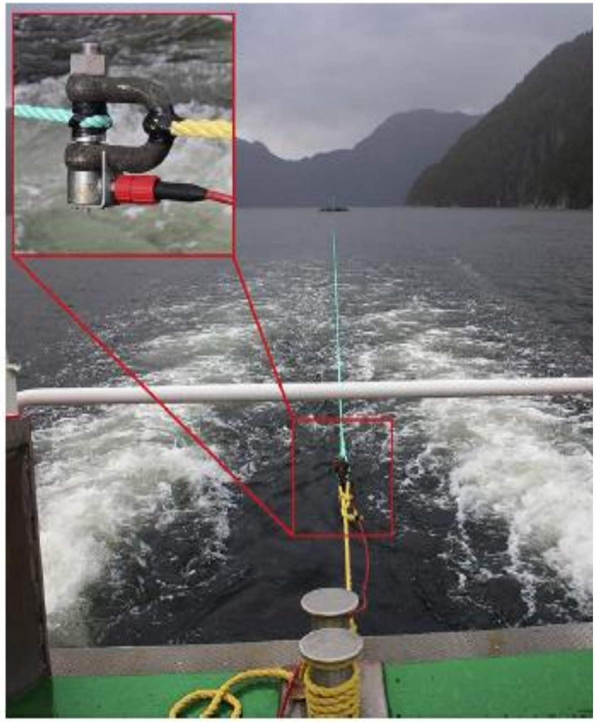
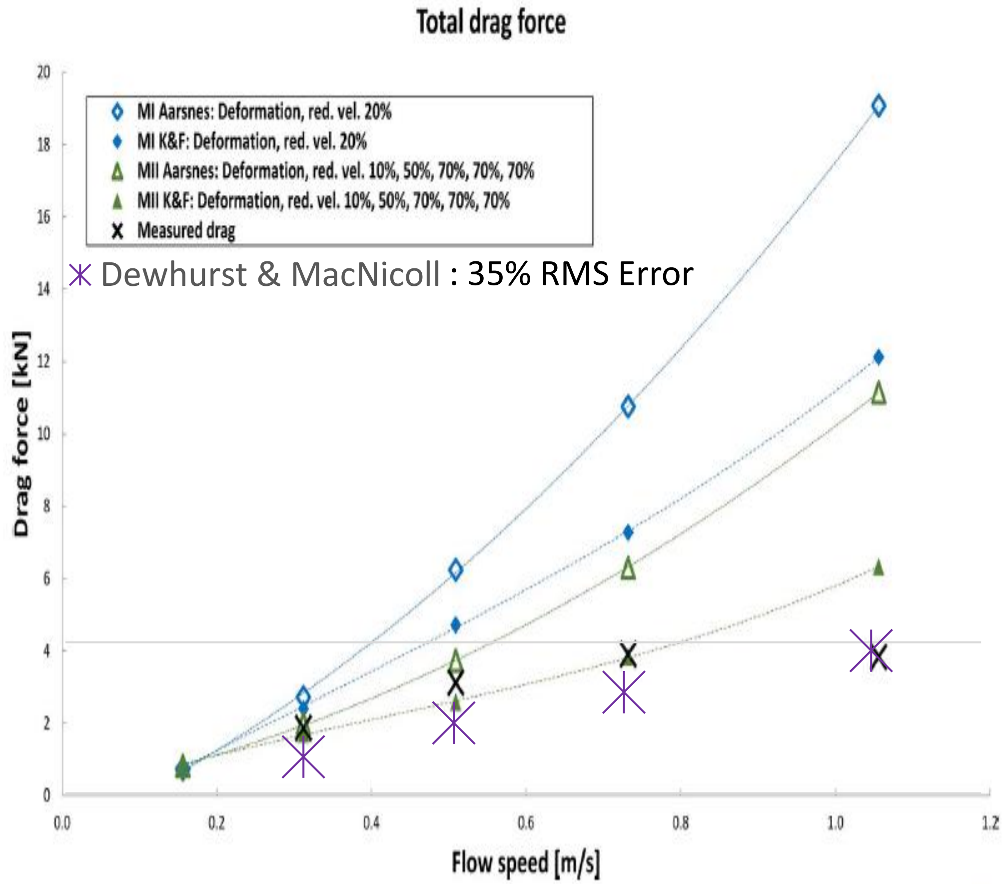


Fig. 3. Towing of the cage system. The cage was towed at a stable speed a
which was ensured by monitoring a mobile network corrected GPS and the st
the 350 m long tow rope and confirmed by a stable current velocity one
stream from the cage system. The detail frame shows the load shackle conn
tow rope.



✳ Dewhurst & MacNicoll : 35% RMS Error

Fig. 9. Drag on the fish cage net at different flow speeds as measured and estimated by methods I (MI) and II (MII) and based on (Aarsnes et al., 1990) (Aarsnes) and (Kristiansen and Faltinsen, 2012) (K&F). X marks the measured drag on the fish cage net, and (empty and filled) ◊ and Δ mark the drag calculated using MI and MII, respectively.

Resolving the term "Offshore"

ICES Working Group on Open-Ocean Aquaculture

Goals:

1. Promote common understanding and avoid misuse for different, partly arbitrary classifications, which can lead to misinterpretation and confusion among different actors, such as NGOs, licensers, and federal agencies;
2. Enable regulators to identify the characteristics of a marine aquaculture site;
3. Allow farmers to assess or quantitatively compare sites for development;
4. Equip developers and producers to identify operational parameters in which the equipment and vessels will need to be operating;
5. Provide insurers and investors with better means to assess risk and premiums;
6. Circumvent the emergence of narratives that root in different cognitive interpretations of the terminology in public discourse arenas.

Buck, B. H., Bjelland, H., Bockus, A., Chambers, M., Costa-Pierce, B. A., Dewhurst, T., Ferreira, J., Føre, H. M., Fredriksson, D., Goseberg, N., Holmyard, J., Isbert, W., Krause, G., Markus, T., Papandroulakis, N., Sclodnick, T., Silkes, B., Strand, Å., Troell, M., Wieczorek, D., van den Burg, S., Heasman, K. . **Resolving the term 'offshore aquaculture' by decoupling 'exposed' and 'distance from shore' for managers and policy makers.** Journal of the World Aquaculture Society. *In preparation.*

Engineering to:

- Prevent disaster
- Improve performance
  - Operations
    - Navigability
    - Ease of install
    - Weather windows
  - Yield
    - Maintain optimal depth
    - Limit storm loss
    - Avoid entanglement
- Reduce costs

2017 Cypress Island
Atlantic Salmon Net Pen Failure:
An Investigation and Review

- As a result of excessive loads on the net pen system created by:
  - currents and net sizes exceeding those specified by the net pen manufacturer,

Dewhurst, 2019

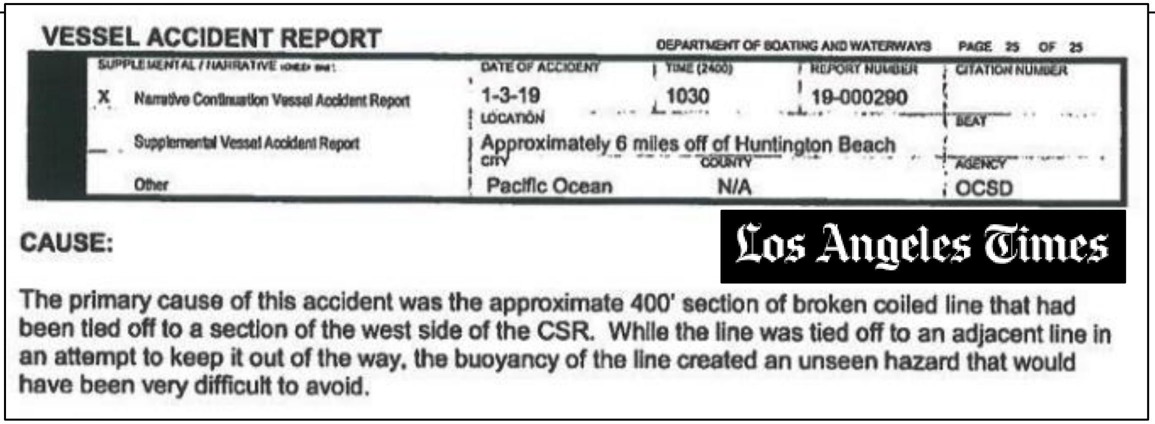
State kills Atlantic salmon farming in Washington

Originally published March 2, 2018 at 4:14 pm | *Updated March 23, 2018 at 9:29 am* ☰ The Seattle Times

RNZ SCIENCE AND ENVIRONMENT STORIES - NEW ZEALAND

MUSSEL FARMERS MILLIONS OF DOLLARS OUT OF POCKET AFTER STORMS

JULY 30, 2021



VESSEL ACCIDENT REPORT

DEPARTMENT OF BOATING AND WATERWAYS PAGE 25 OF 25

SUPPLEMENTAL / NARRATIVE (CHECK ONE)
X Narrative Continuation Vessel Accident Report
_ Supplemental Vessel Accident Report
Other

DATE OF ACCIDENT: 1-3-19
TIME (2400): 1030
REPORT NUMBER: 19-000290
CITATION NUMBER:
LOCATION: Approximately 6 miles off of Huntington Beach
BEAT:
CITY: Pacific Ocean
COUNTY: N/A
AGENCY: OCSD

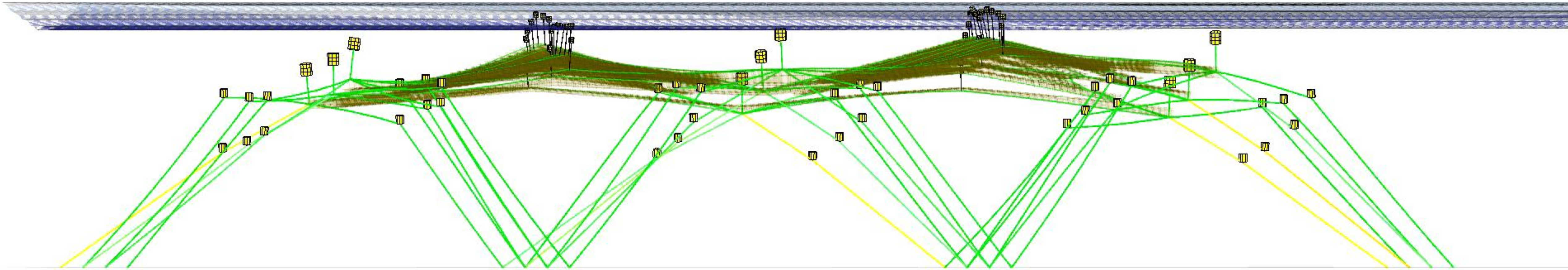
CAUSE:

Los Angeles Times

The primary cause of this accident was the approximate 400' section of broken coiled line that had been tied off to a section of the west side of the CSR. While the line was tied off to an adjacent line in an attempt to keep it out of the way, the buoyancy of the line created an unseen hazard that would have been very difficult to avoid.

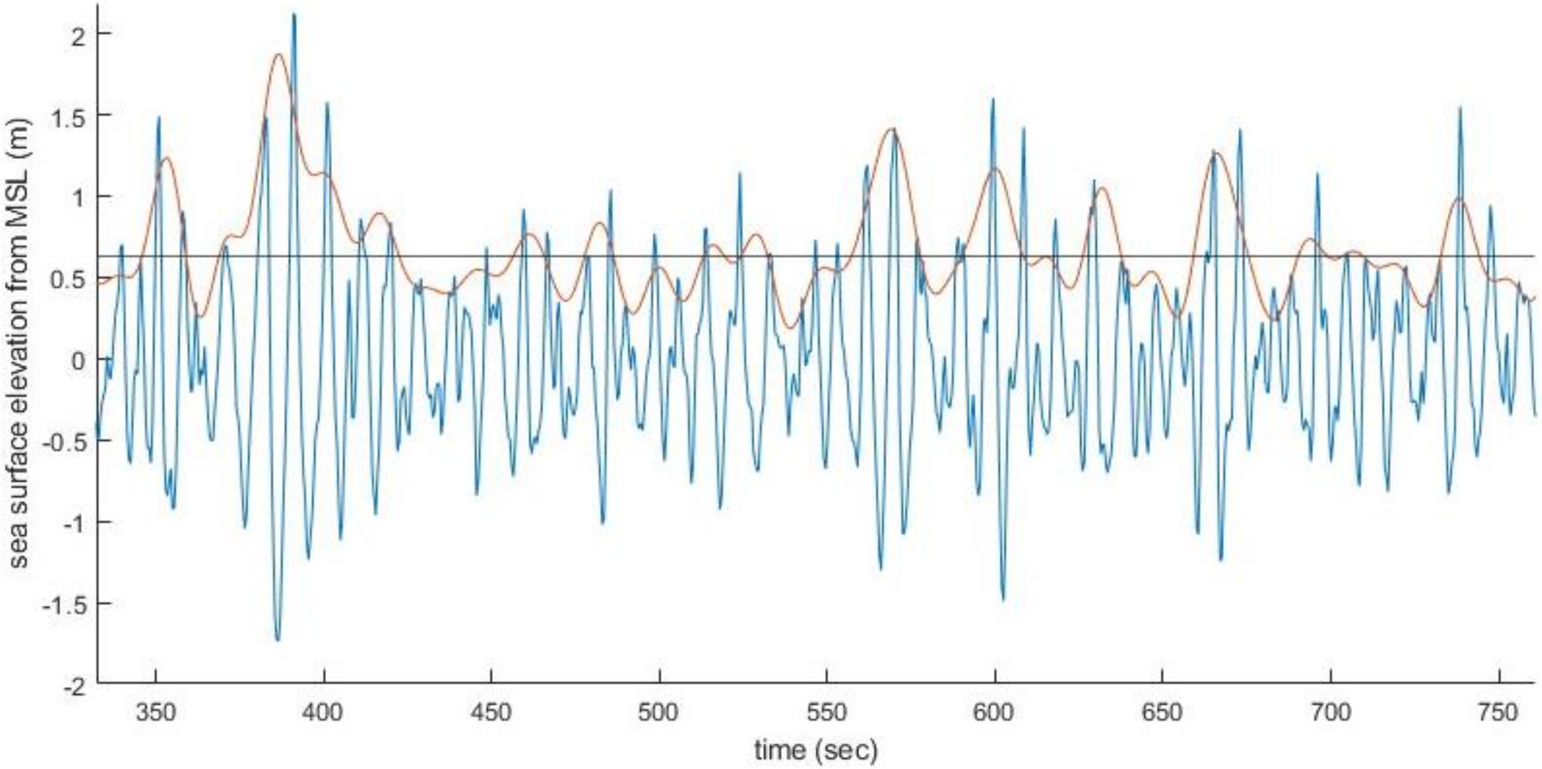
Nonlinear Physics: Low-frequency Tension Oscillations

- Observed in both model predictions and full-scale, *in-situ* measurements



Nonlinear Physics: Low-frequency Tension Oscillations

- Defined wave group envelope according to List (1991)
- Correlation of mean period of low frequency response and average envelope period
- Regression models showed correlation of low frequency tension response with wave group envelop heights



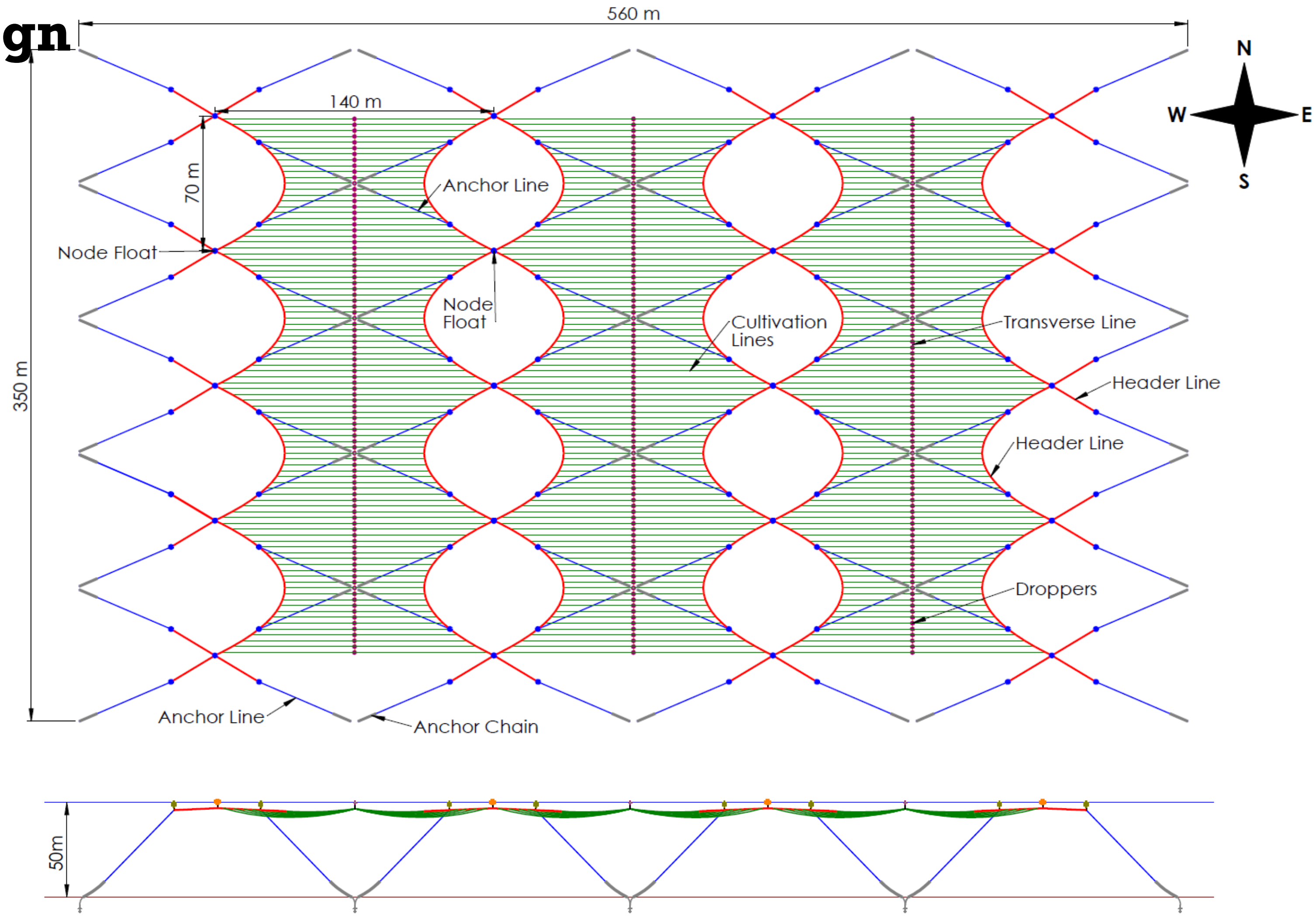
Load case Number	1	2	3	4	5	6	7	8	9
Envelope mean period $T_{m,env}$ (sec)	28	31	25	23	29	31	21	24	29
Low frequency tension $T_{m,F,low}$ (sec)	26	32	26	28	31	30	26	28	28

Moscicki, Z., Swift, M.R., Dewhurst, T., MacNicoll, M., Fredriksson, D., Tsukrov, I., & Chambers, M. (*In preparation*). Evaluation of an experimental kelp farm's structural behavior using regression modelling and response amplitude operators derived from in-situ measurements. Aquaculture Engineering.

Commercial Scale Farm Design

- 50 m water depth
- 140 x 70 m (~1 hectare) tiles
- 4 x 3 *tile* array
- 3 m cultivation line spacing

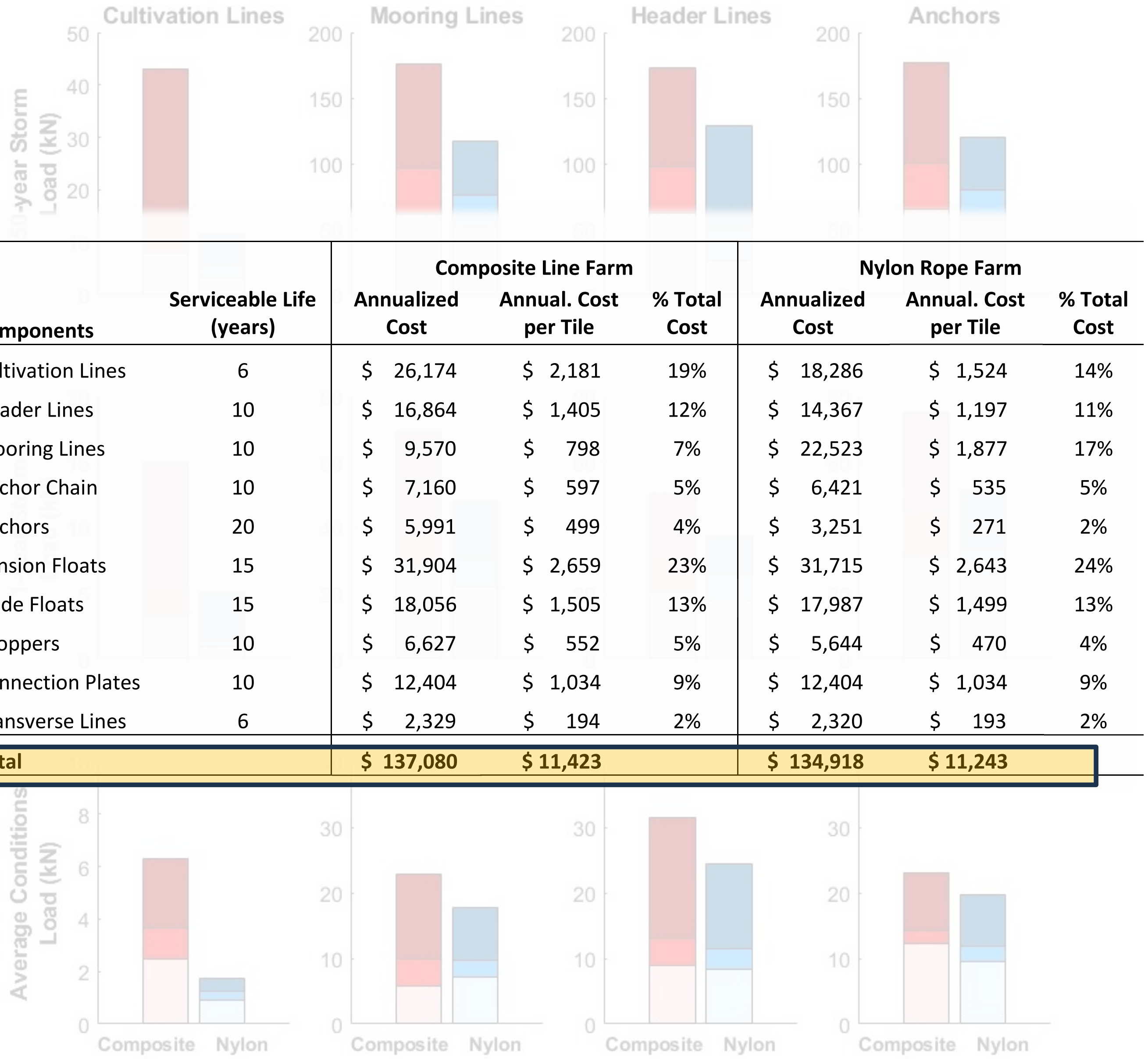
Farm Variant	Mooring Lines	Cultivation Lines
Composite Line Farm	**fiberglass** rebar	fiberglass rebar
Nylon Rope Farm	12 plait **nylon** rope	3 strand nylon rope



Moscicki, Z., Dewhurst, T., & MacNiccoll, M. (*In preparation*). Structural and economic implications of using composite rods to replace ropes in offshore seaweed farms to mitigate risk of marine animal entanglement. Aquaculture Engineering.

Economic Analysis

- Extracted statistics for each component and load case type:
    - Extreme loads
    - Significant load magnitudes
    - Mean loads
- Loads higher for the composite line farm
- Annualized structural capital costs for the composite line farm were near parity



Components	Serviceable Life (years)	Composite Line Farm: Annualized Cost	Composite Line Farm: Annual. Cost per Tile	Composite Line Farm: % Total Cost	Nylon Rope Farm: Annualized Cost	Nylon Rope Farm: Annual. Cost per Tile	Nylon Rope Farm: % Total Cost
Cultivation Lines	6	$ 26,174	$ 2,181	19%	$ 18,286	$ 1,524	14%
Header Lines	10	$ 16,864	$ 1,405	12%	$ 14,367	$ 1,197	11%
Mooring Lines	10	$ 9,570	$ 798	7%	$ 22,523	$ 1,877	17%
Anchor Chain	10	$ 7,160	$ 597	5%	$ 6,421	$ 535	5%
Anchors	20	$ 5,991	$ 499	4%	$ 3,251	$ 271	2%
Tension Floats	15	$ 31,904	$ 2,659	23%	$ 31,715	$ 2,643	24%
Node Floats	15	$ 18,056	$ 1,505	13%	$ 17,987	$ 1,499	13%
Droppers	10	$ 6,627	$ 552	5%	$ 5,644	$ 470	4%
Connection Plates	10	$ 12,404	$ 1,034	9%	$ 12,404	$ 1,034	9%
Transverse Lines	6	$ 2,329	$ 194	2%	$ 2,320	$ 193	2%
Total		**$ 137,080**	**$ 11,423**		**$ 134,918**	**$ 11,243**	

Moscicki, Z., Dewhurst, T., & MacNicoll, M. (*In preparation*). Structural and economic implications of using composite rods to replace ropes in offshore seaweed farms to mitigate risk of marine animal entanglement. Aquaculture Engineering.

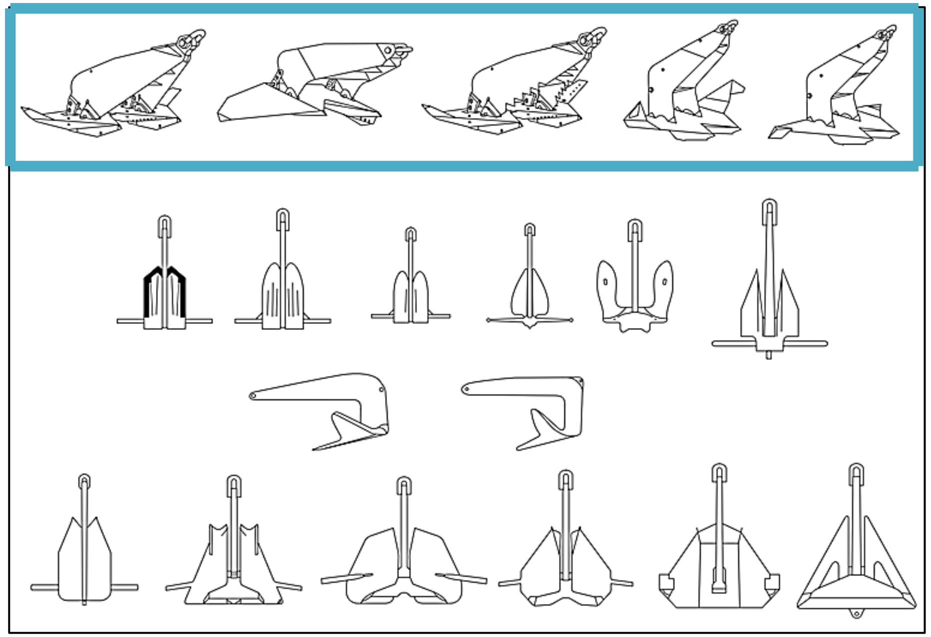
Validation – Ocean Rainforest Inc.

Photo Credit: William Klingbeil. Sponsored by US DOE ARPA-e MARINER via Ocean Rainforest

Anchoring

1. Compute *design capacity*
   - Loads from simulation
   - Apply holding factor
2. Decide on anchor type
   - High efficiency drag embedment
3. Determine minimum anchor size
   - Account for *soil type*
   - Account for *uplift*
4. Installation is 12% of total project cost

	Anchor Mass
Design A	-
Design B	30% larger
Design C	85% larger



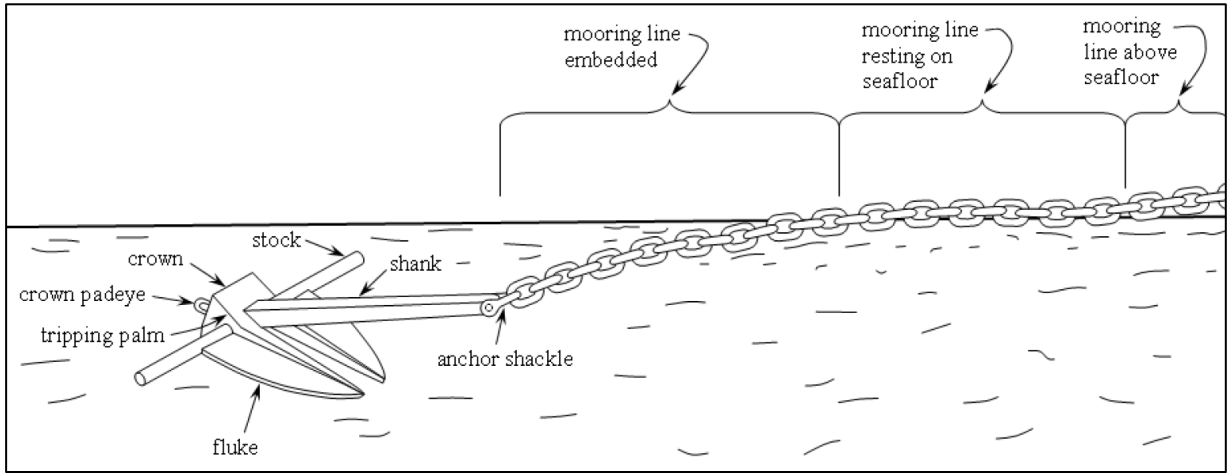
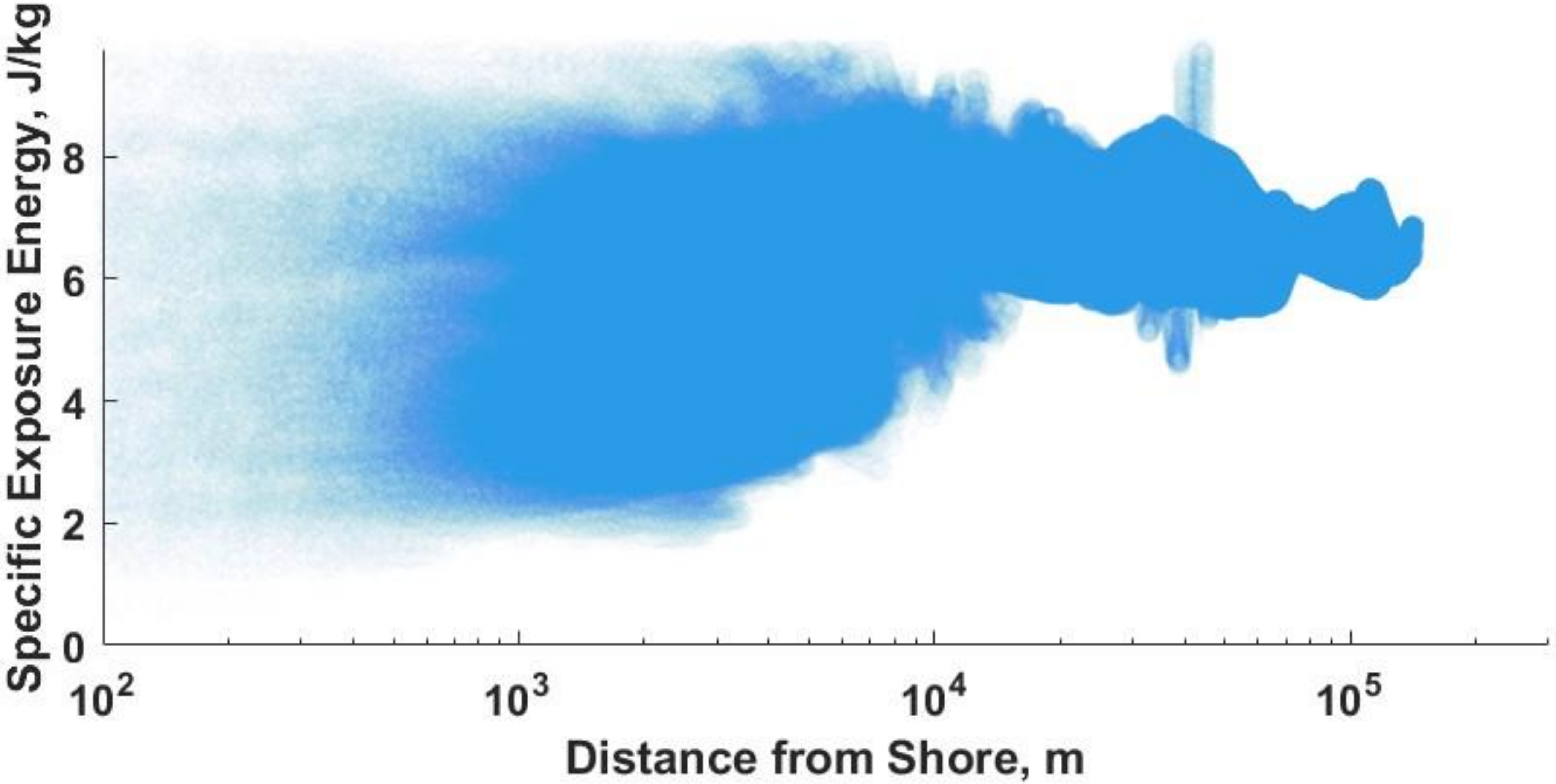


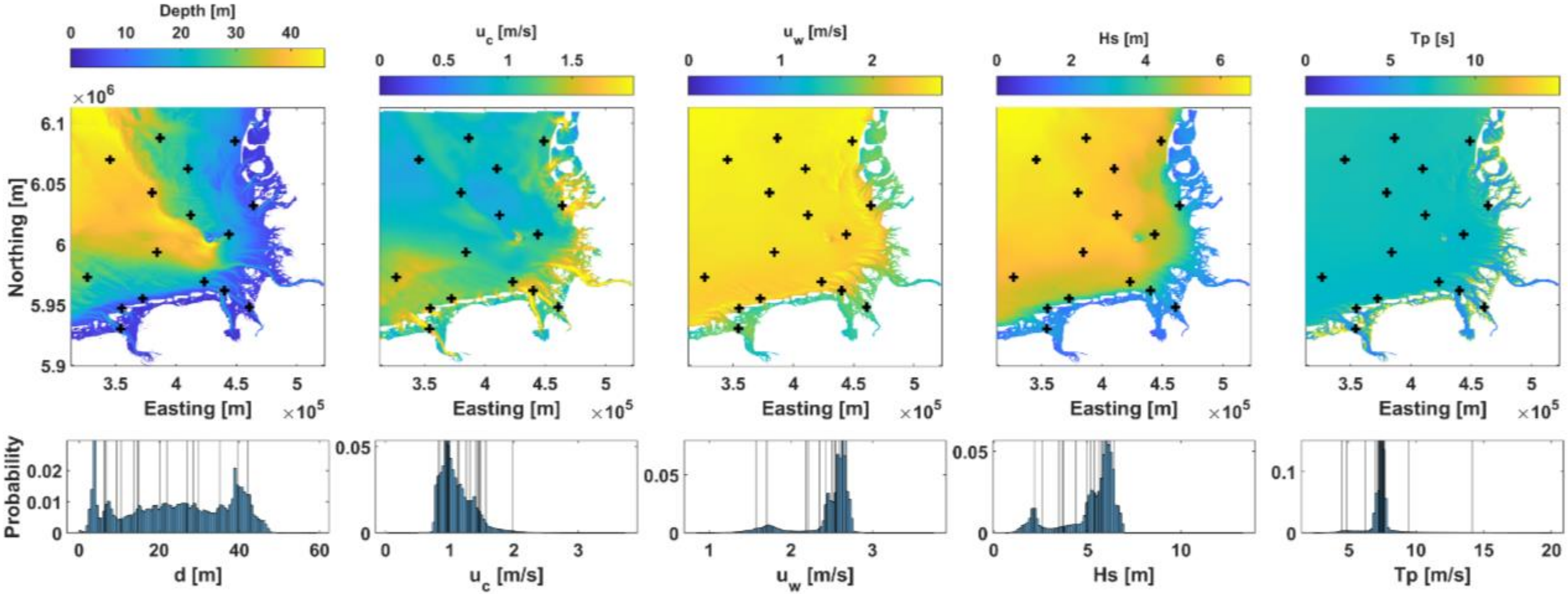
Figure source: American Petroleum Institute, 2008.

Exposure vs. Distance



The Cost of Exposure Energy:

Correlating Exposure Index to $CapEx



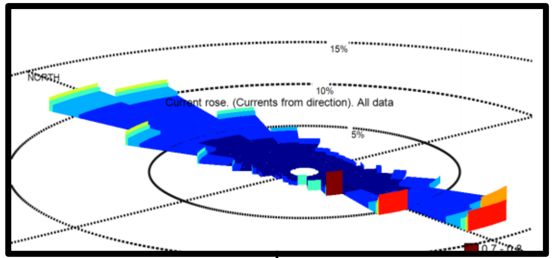
Lojek, O. Goseberg, N., Moe Fore, H., **Dewhurst, T.**, Bölker, T, Heasman, K, Buck, B, Fredriksson, DW, Rickerich, S, A quantified approach to assessing hydrodynamic exposure of mariculture sites. Journal of the World Aquaculture Society. *In preparation.*

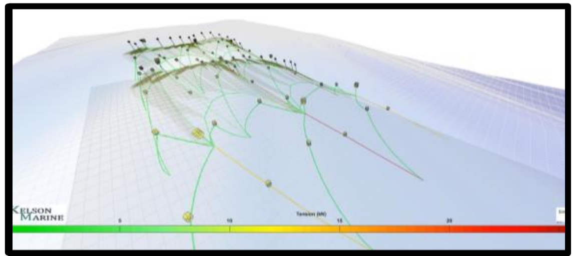
Now we can engineer with *confidence*

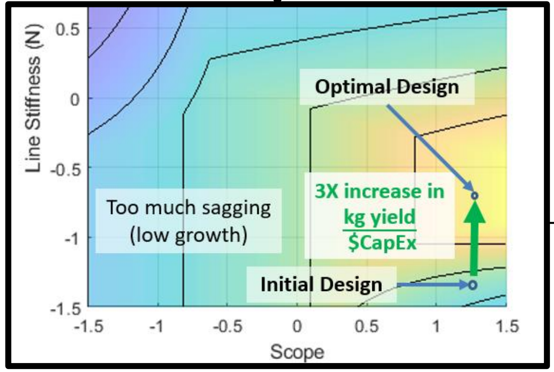
Identify requirements

Quantify structural response and performance

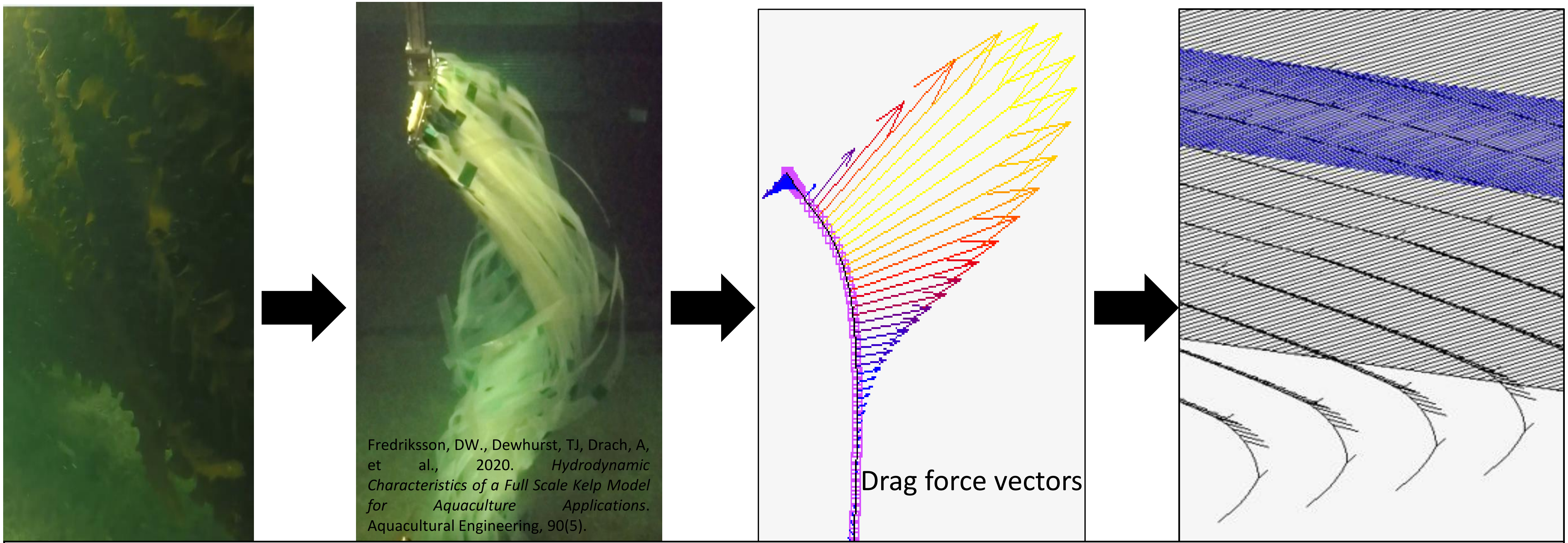
Design, and optimize economics







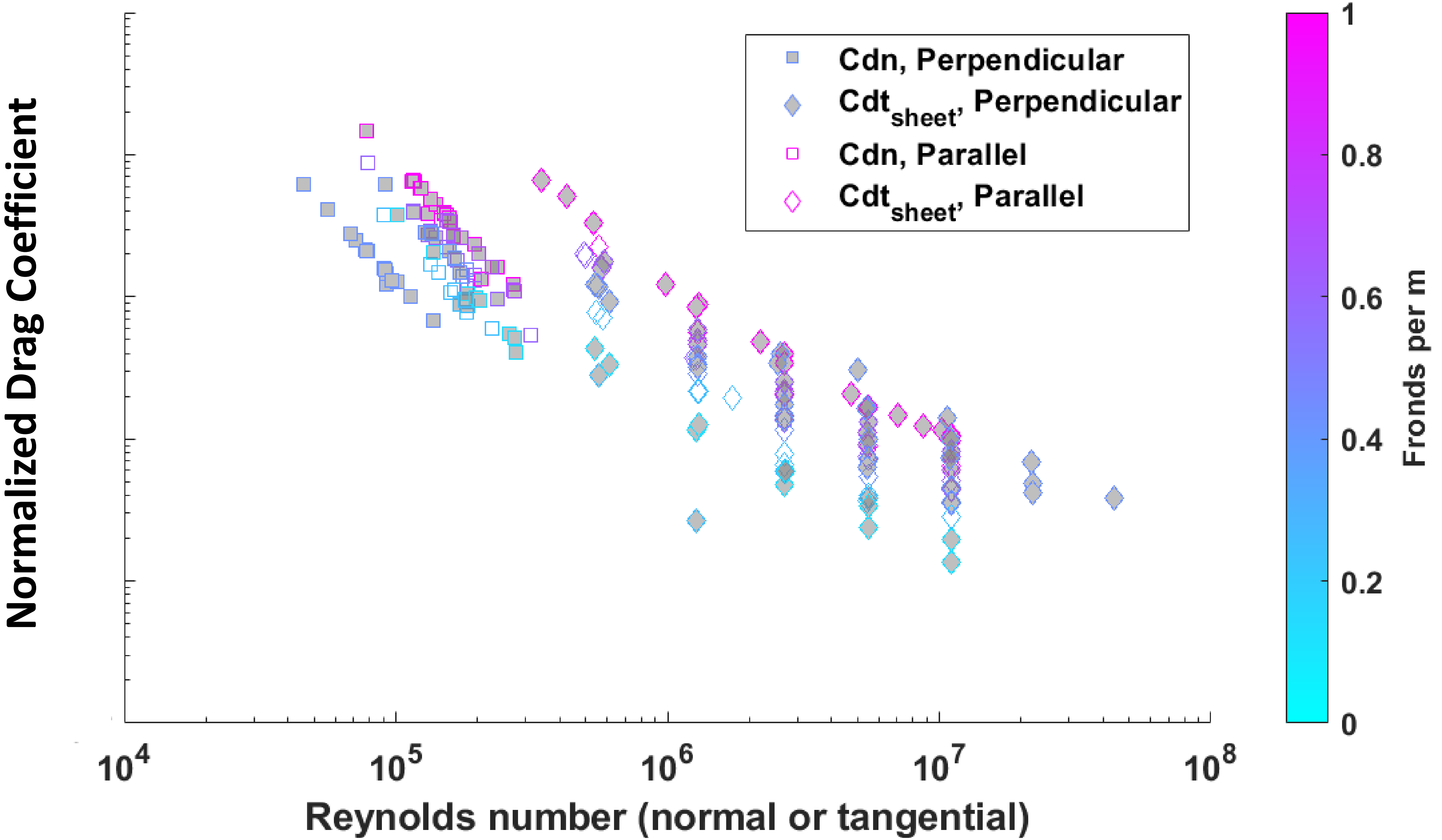
Hydro-/Structural Dynamic FEA



Fredriksson, DW., Dewhurst, TJ, Drach, A, et al., 2020. *Hydrodynamic Characteristics of a Full Scale Kelp Model for Aquaculture Applications.* Aquacultural Engineering, 90(5).

$$\boldsymbol{f} = \frac{1}{2}\rho D_{\mathbf{n}} C_n |\boldsymbol{V_{Rn}}| \boldsymbol{V}_{\boldsymbol{Rn}}^{\beta_{\mathrm{n}}-1} + \frac{1}{2}\rho D_{\boldsymbol{t}} C_t |\boldsymbol{V_{Rt}}| \boldsymbol{V}_{\boldsymbol{Rt}}^{\beta_{\mathrm{t}}-1} + \rho A \dot{\boldsymbol{V}}_{\boldsymbol{n}} + \rho A C_a \dot{\boldsymbol{V}}_{\boldsymbol{Rn}} \, .$$

Macrocystis Drag Coefficients



Economic Analysis

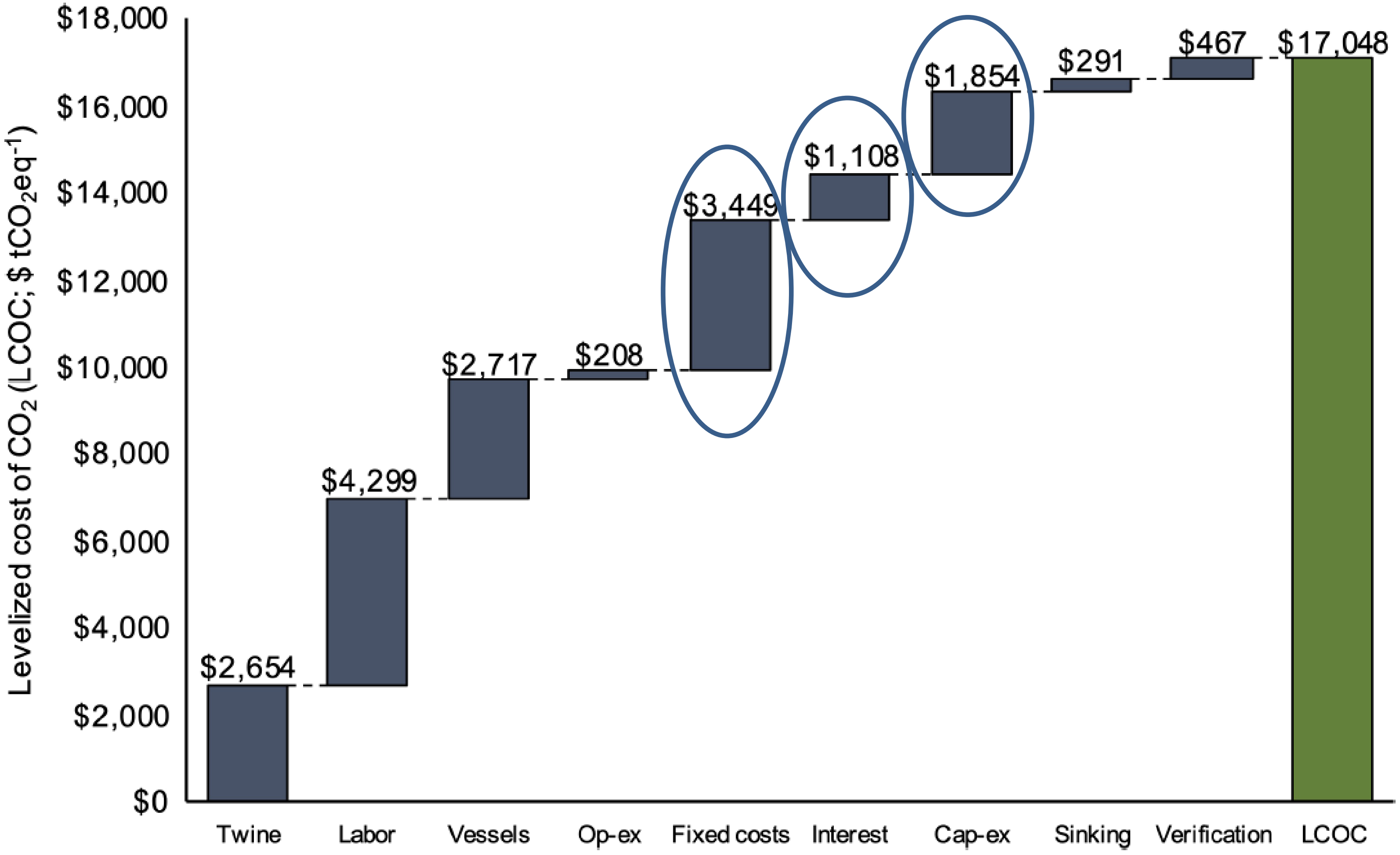
- Applied specification procedures indicated by Norwegian Aquaculture Standard
- Estimated annualized costs, based on:
  - Quotes from vendors
  - Material use and 75% profit margin
  - Typical serviceable lifetimes

		Composite Line Farm			Nylon Rope Farm		
Components	**Serviceable Life (years)**	**Annualized Cost**	**Annual. Cost per Tile**	**% Total Cost**	**Annualized Cost**	**Annual. Cost per Tile**	**% Total Cost**
Cultivation Lines	6	$ 26,174	$ 2,181	19%	$ 18,286	$ 1,524	14%
Header Lines	10	$ 16,864	$ 1,405	12%	$ 14,367	$ 1,197	11%
Mooring Lines	10	$ 9,570	$ 798	7%	$ 22,523	$ 1,877	17%
Anchor Chain	10	$ 7,160	$ 597	5%	$ 6,421	$ 535	5%
Anchors	20	$ 5,991	$ 499	4%	$ 3,251	$ 271	2%
Tension Floats	15	$ 31,904	$ 2,659	23%	$ 31,715	$ 2,643	24%
Node Floats	15	$ 18,056	$ 1,505	13%	$ 17,987	$ 1,499	13%
Droppers	10	$ 6,627	$ 552	5%	$ 5,644	$ 470	4%
Connection Plates	10	$ 12,404	$ 1,034	9%	$ 12,404	$ 1,034	9%
Transverse Lines	6	$ 2,329	$ 194	2%	$ 2,320	$ 193	2%
Total		**$ 137,080**	**$ 11,423**		**$ 134,918**	**$ 11,243**	

Results

Breakdown of annual expenses within the baseline BTEM for LCOCarbon ($ tCO2eq-1).

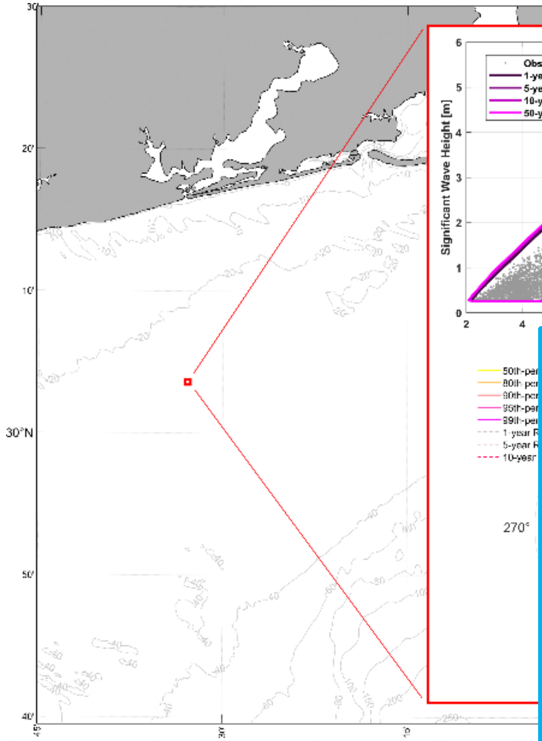
- Hyper-realistic costing with engineering analysis incorporated
- In Maine state waters
- Using baseline technology



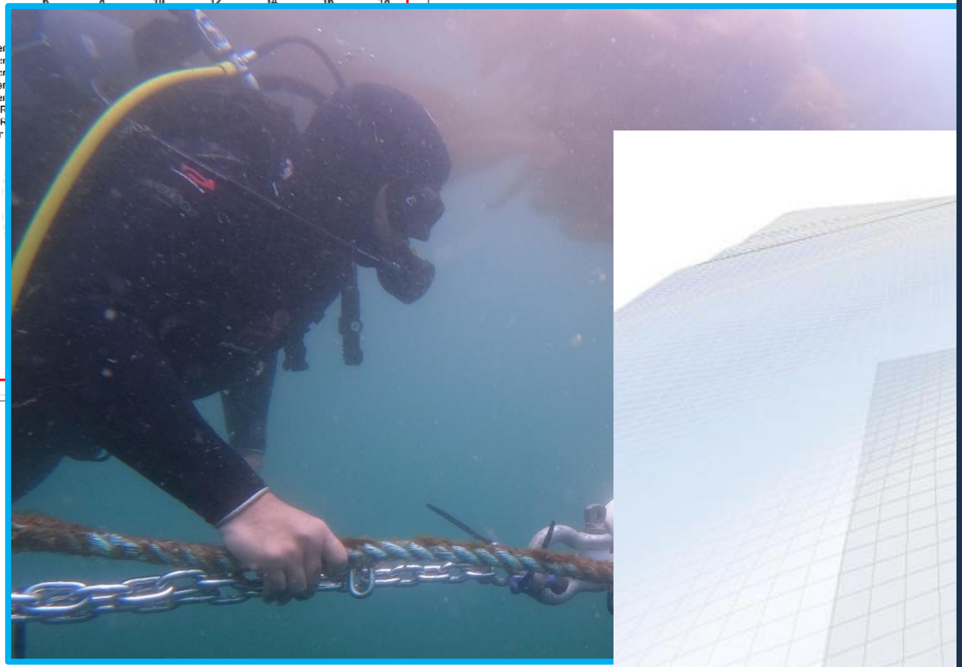
Coleman, S., Dewhurst, T., Fredriksson, D. W., St. Gelais, A. T., Cole, K. L., MacNicoll, M., Laufer, E., & Brady, D. C. (2022). *Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal*. Frontiers.

Rigorous ocean analysis and risk quantification

“Smart Farming”



Field-validated methods



Recommended design practice

for offshore & nearshore

Seaweed growing systems

Version 1.0 2023

Document information

Date	: 30 March 2023
Company	: Aqitec
Client	: Invest-NL
Version	: 1.0
Document status	: Released version
Classification	: Report
Nr of pages	: 31
Written by	: I.W. Wieling, I.S. Wieling
Project approval	: North Sea Farmers E. Brouwers
Detailed approval	: Van Oord Offshore
Basic approval and verification	: DNV

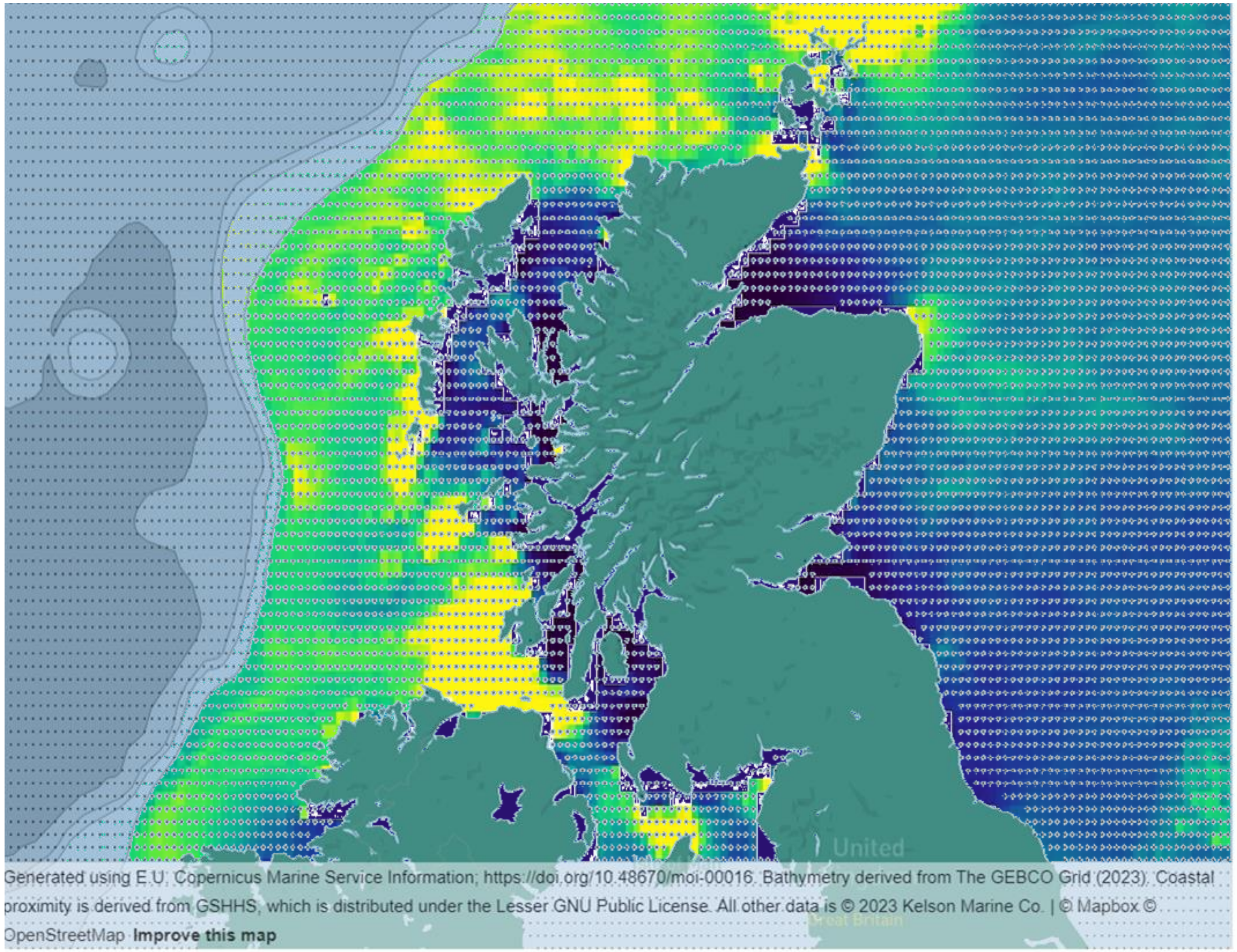
NORTH SEA FARMERS

Van Oord
Marine ingenuity

DNV

KELSON MARINE

Exposure Index: Resources



Generated using E.U. Copernicus Marine Service Information; https://doi.org/10.48670/moi-00016. Bathymetry derived from The GEBCO Grid (2023). Coastal proximity is derived from GSHHS, which is distributed under the Lesser GNU Public License. All other data is © 2023 Kelson Marine Co. | © Mapbox © OpenStreetMap **Improve this map**