Ocean Thermal Energy Conversion (OTEC)
&
Wave Energy Conversion (WEC)
for
Pacific Island Nations
&
Asian Developing Nations

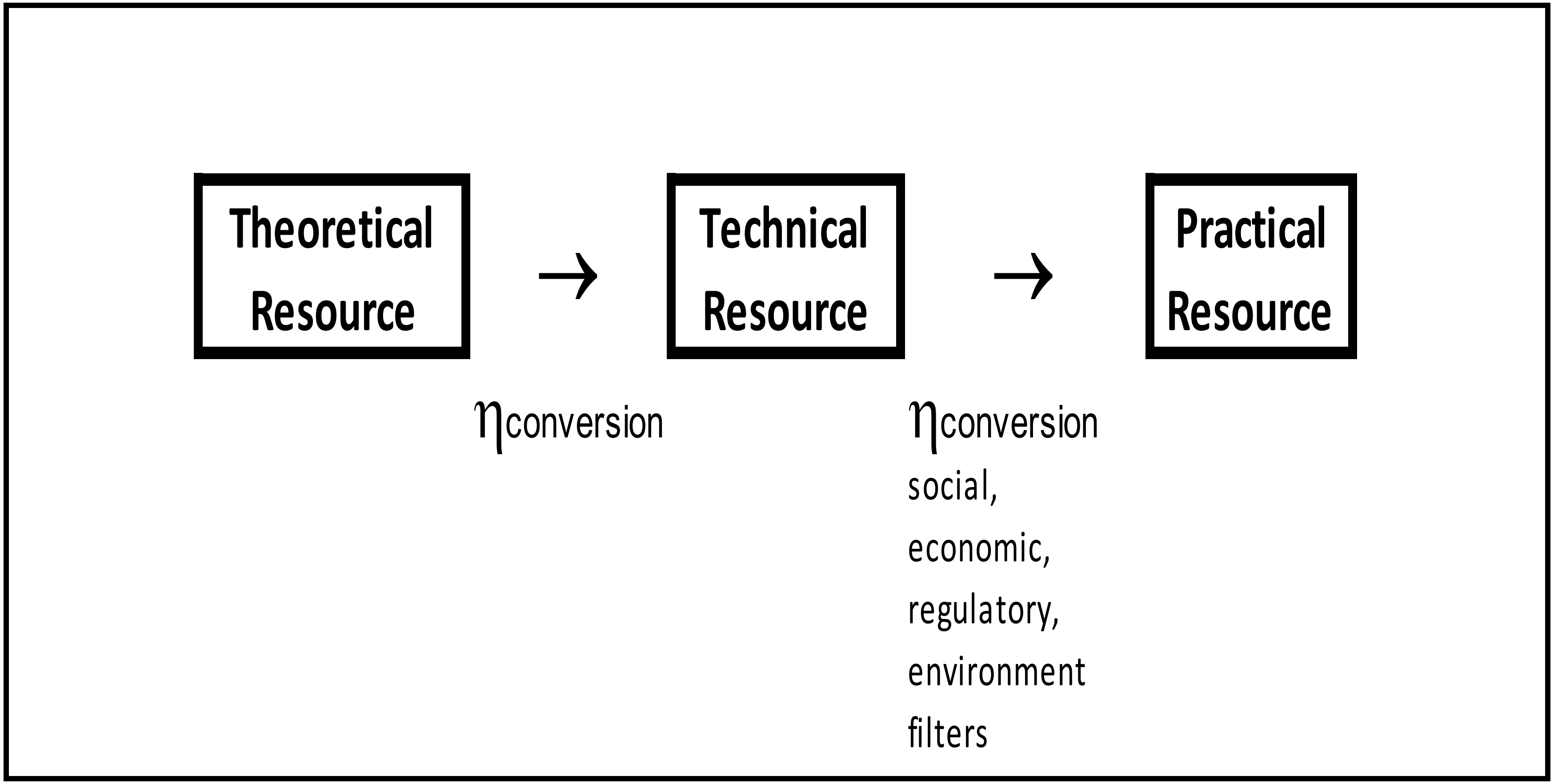
Luis A. Vega, Ph.D.

University of Hawaii

luisvega@hawaii.edu

July 30, 2014

Resource Nomenclature (DOE)



Theoretical Resource → **_Transfer Function_** → Technical Resource

Ocean Thermal

RESOURCE	***Transfer Function***	PRODUCT
$\Delta T\ (^\circ C) = T_{20m} - T_{1000m}$	Public Domain	kWh; H_2O; AC
Ocean Volume	24/7	

Waves

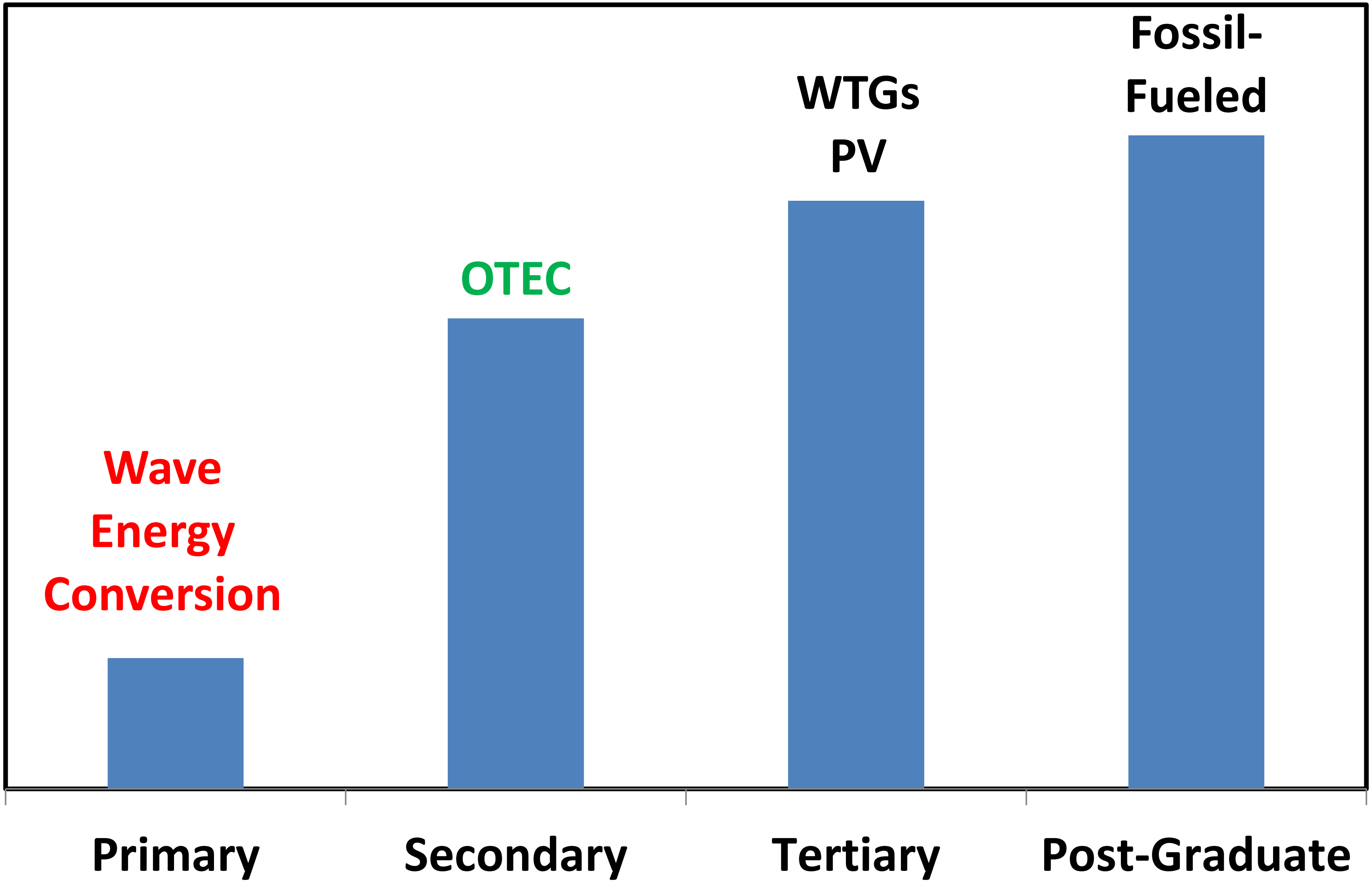
RESOURCE	***Transfer Function***	PRODUCT
$P_0(kW/m) = f(Hs, Te, D; \theta)$	Proprietary	kWh
Ocean Area	not 24/7	

Theoretical Resource Availability?

Developing Nation	Wave Energy	OTEC Resource
CENTRAL & WEST ASIA		
Pakistan	No	No
EAST ASIA		
People's Republic of China	No	Yes
PACIFIC		
Cook Is.	Yes	Yes
Fiji Islands	Yes	Yes
Kiribati	No	Yes
Marshall Islands	Yes	Yes
Federated States of Micronesia	Yes	Yes
Nauru	Yes	Yes
Palau	No	Yes
Papua New Guinea	No	Yes
Samoa	Yes	Yes
Solomon Islands	No	Yes
Timor-Leste	No	Yes
Tonga	Yes	Yes
Tuvalu	Yes	Yes
Vanuatu	Yes	Yes
SOUTH ASIA		
Bangladesh	No	No
India	Yes	Yes
Maldives	Yes	Yes
Sri Lanka	Yes	Yes
SOUTHEAST ASIA		
Brunei Darussalam	No	Yes
Cambodia	No	No
Indonesia	Yes	Yes
Malaysia	No	Yes
Myanmar	No	Yes
Philippines	Yes	Yes
Thailand	No	Yes
Viet Nam	No	Yes

Technology Readiness Level

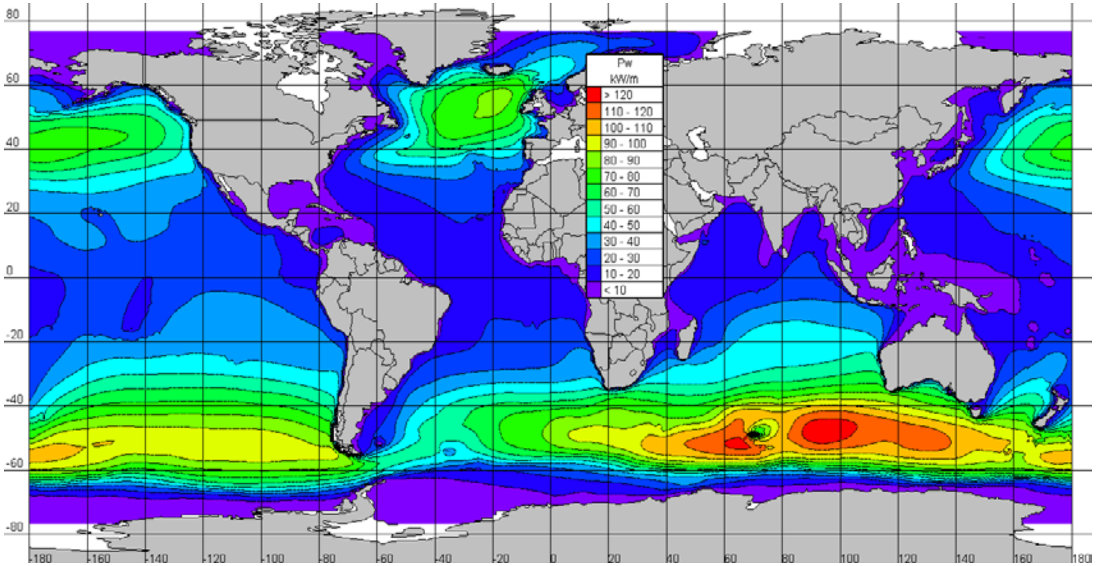
("educational level" analogy)



Wave Resources

- **<u>Theoretical</u>** estimates from two numerical wind-wave models: *annual averages of offshore-wave-power-flux (kW/m);*
- Modeling and correlating offshore resource with the near-shore resource off Hawaii as reference;
- Only a TBD fraction of the **theoretical** resource can be converted into electricity;
- At this stage, nations with annual **theoretica**l averages above 10 kW/m ought to be considered for nearshore modeling; and, in-situ wave measurements in water of ~ 50 m depth and no more than 1 to 3 km from the shoreline & electricity distribution grid;

→ Most Pacific Island Nations, India, Maldives, Sri Lanka, Indonesia and the Philippines.

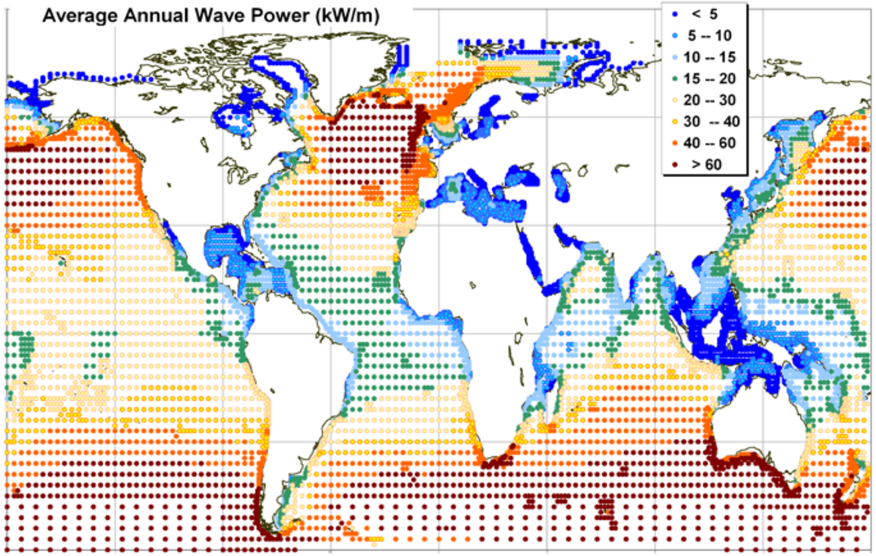


Wave Watch Model

Theoretical Resource: *Deep Water Annual Wave Power Flux (kW/m)*

Input: 1997-2006 Wind Records
Wind-Wave Models calibrated with satellite altimeter data and buoy data

WorldWaves Model



Wave Energy Siting: Technical Aspects

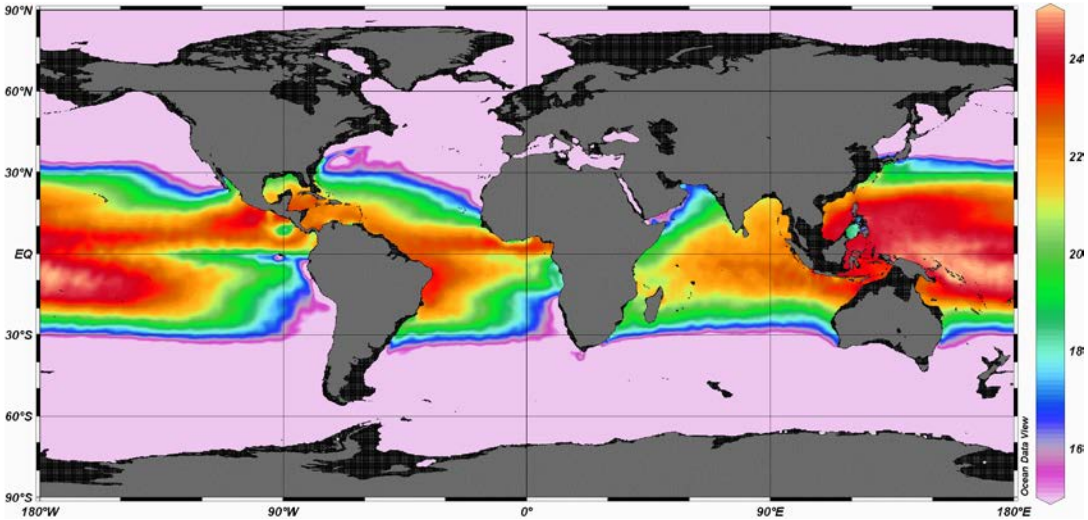
- Water depths < 80 m
- Identify costal segments with highest annual power flux (kW/m)
- Equipment must survive extreme events
- Optimize distance to distribution grid

OTEC Resources

- Technology validated with experimental plants $\rightarrow$ **technical** resource, expressed as electrical energy generated with OTEC plant, can be estimated from the **theoretical** thermal resource: *ΔT between surface waters and water from 1000 m depth*;
- Annual production (GWh) with 100 MW OTEC plant located within EEZ was estimated $\rightarrow$ nations with the potential to generate at least 1000 GWh/year are proposed for further consideration;
- A 10 MW plant (appropriate for smaller Pacific Islands) would generate 1/10 of the values given.

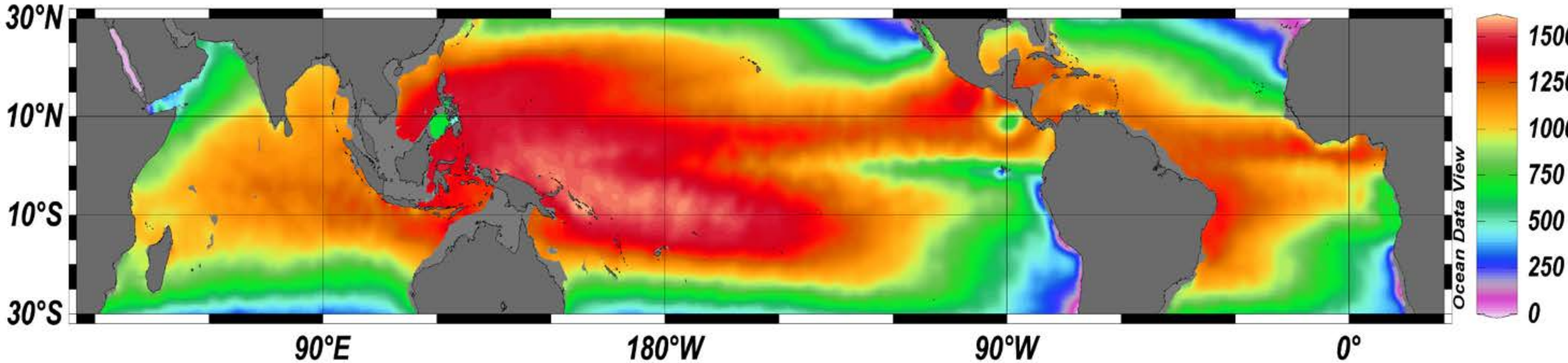
$\rightarrow$ OTEC technology applicable for the majority of nations that are not landlocked.

Ocean Thermal (OTEC) Resource



Color palette
15°C to 25°C

Theoretical Resource: World Ocean Atlas (WOA) Annual Average ΔT ($T_{20m} - T_{1000m}$)



Technical Resource: 100 MW OTEC Plant Annual Electricity Generation (GWh)

Baseline: 877 GWh/year @ ΔT = 20 ℃

OTEC Siting: Technical Aspects

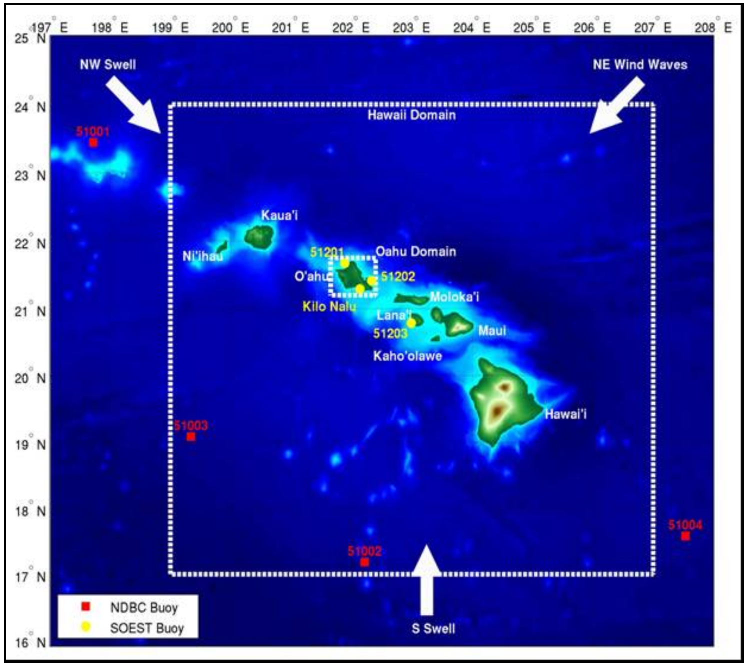
- Offshore beyond 1000 m depth contour
- *In Hawaii, for example, leeward side better thermal resource (ΔT, °C)*
- Optimize distance to distribution grid (e.g., 10 to 20 km)

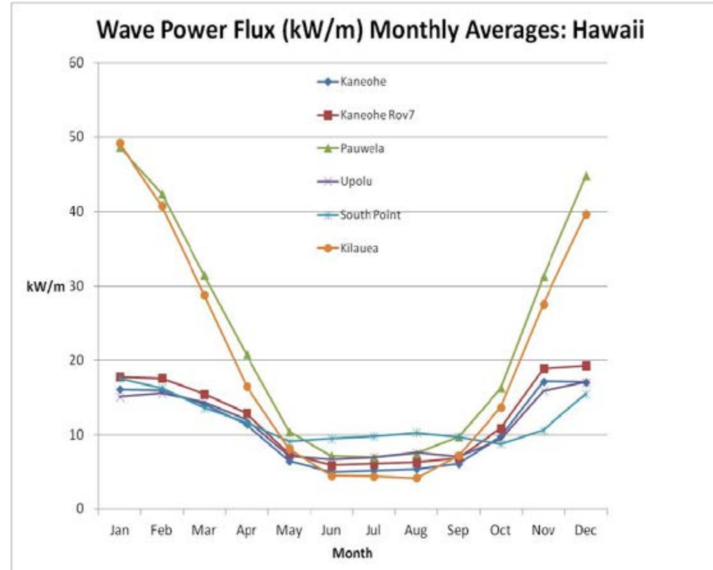
Environmental Impact

- Goal: inputs to Environmental Impact Statement required for permitting & licensing
- Define **differences between ocean energy systems and already established regulated industrial activities**:
- **OTEC key differentiator**: return of large amounts of deep seawater below the photic zone
- **WEC key differentiator**: effect of arrays/farms over large coastal region (*spacing and quantity*)

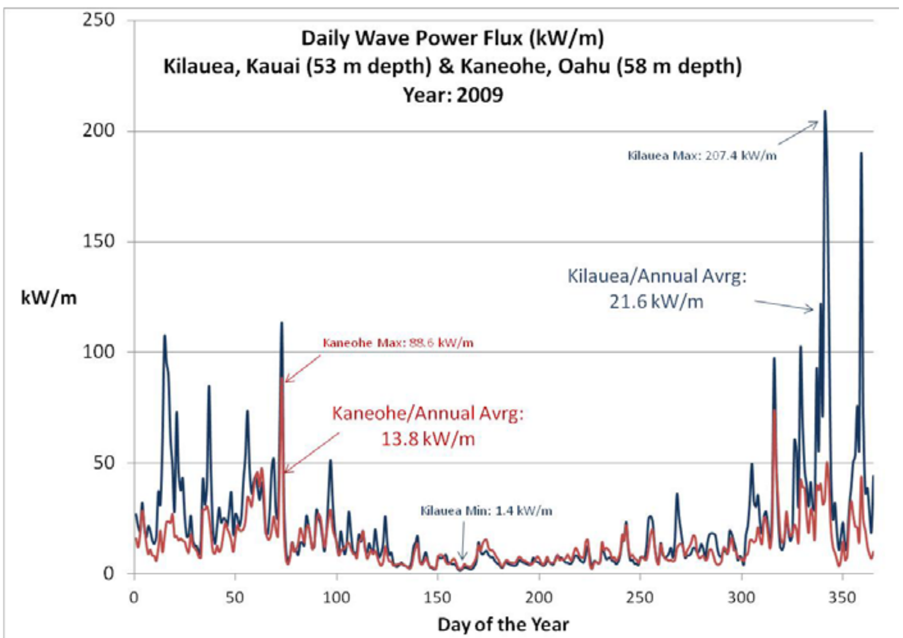
Hawaii Case Study:

Offshore Wave Climate + Bathymetry → Nearshore Wave Climate





Monthly Nearshore

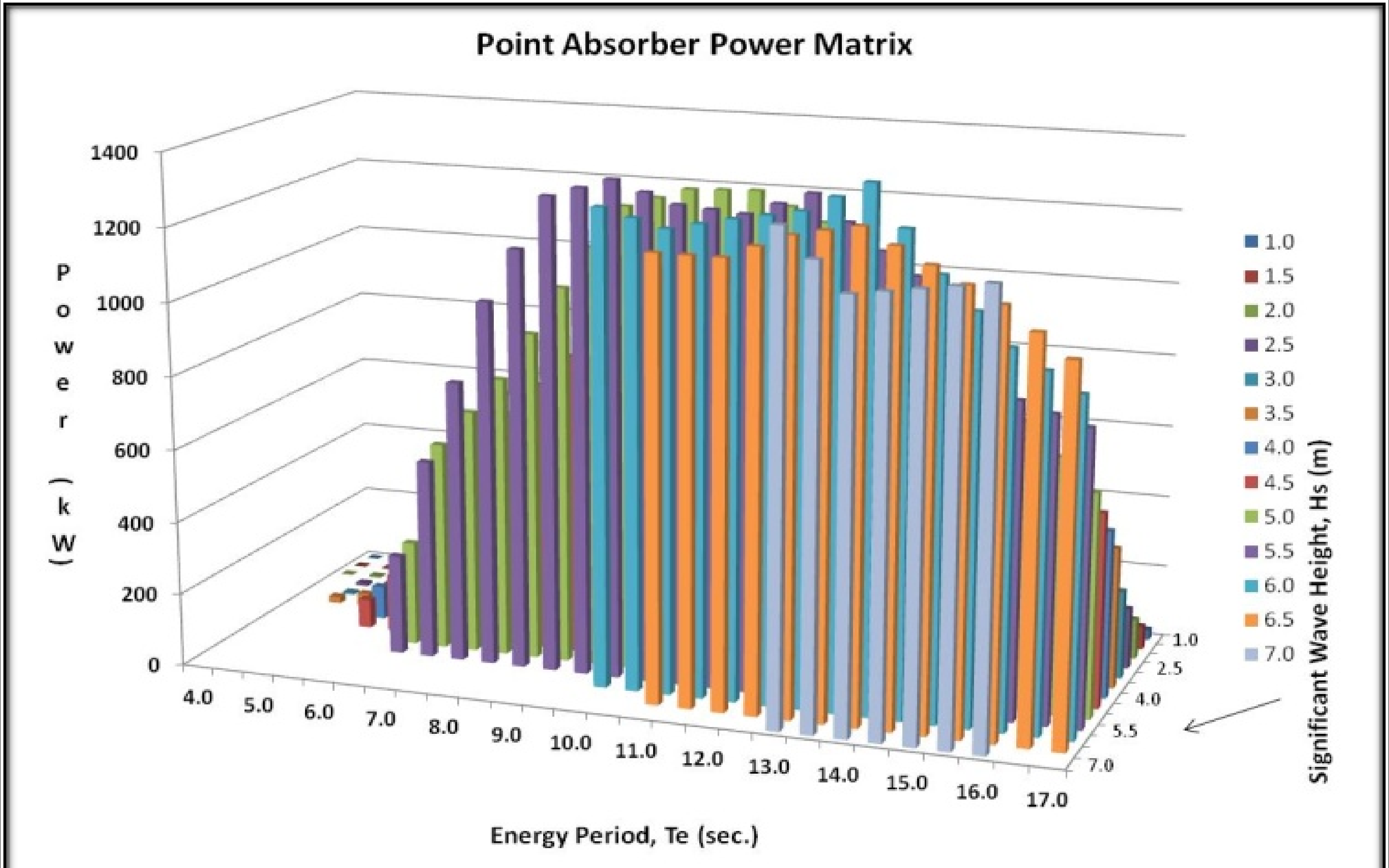


Daily Nearshore

Theoretical Wave Resource

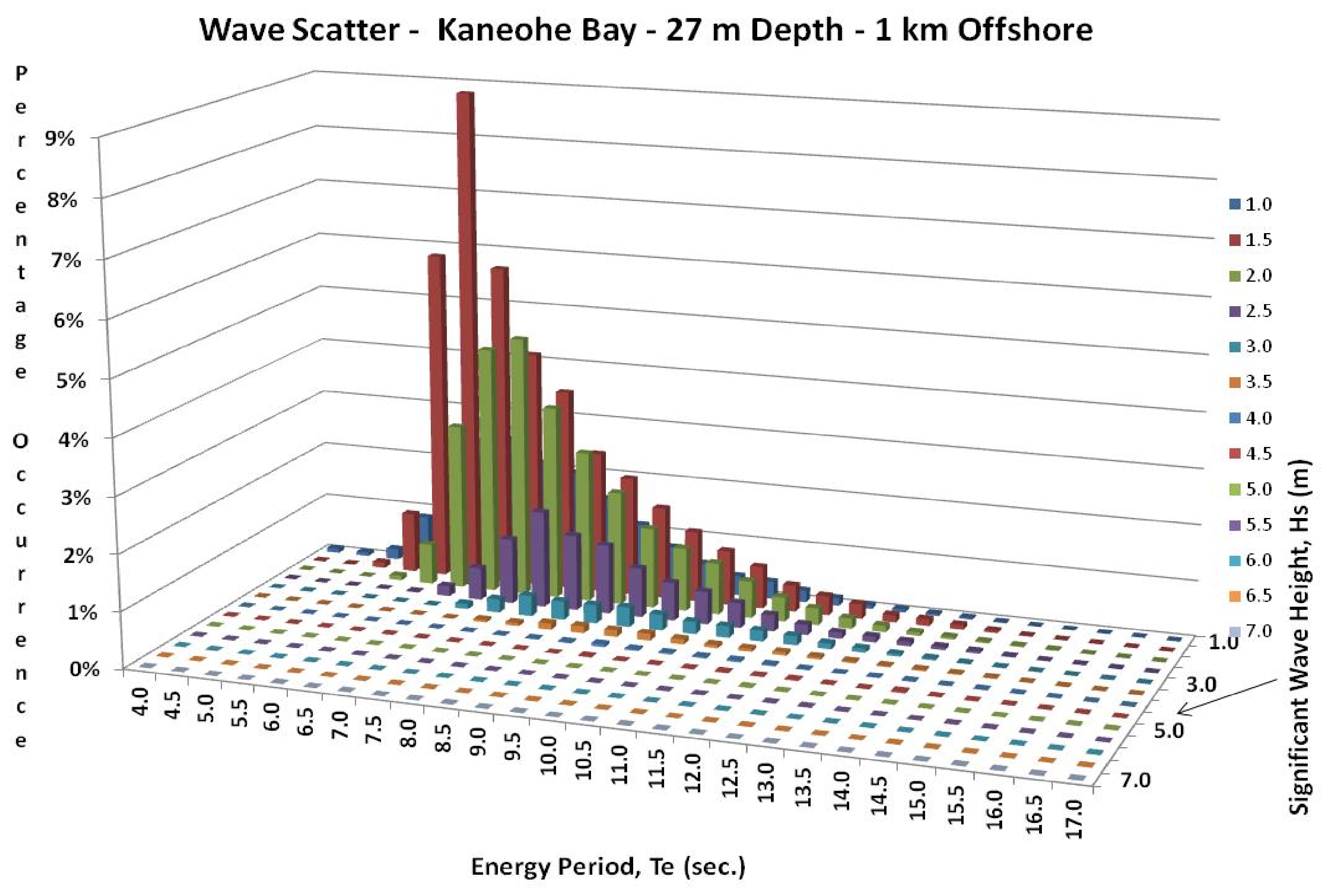
Wave Energy Conversion (WEC) Device Performance

Power Matrix *x Wave Scatter = Electricity Generation*



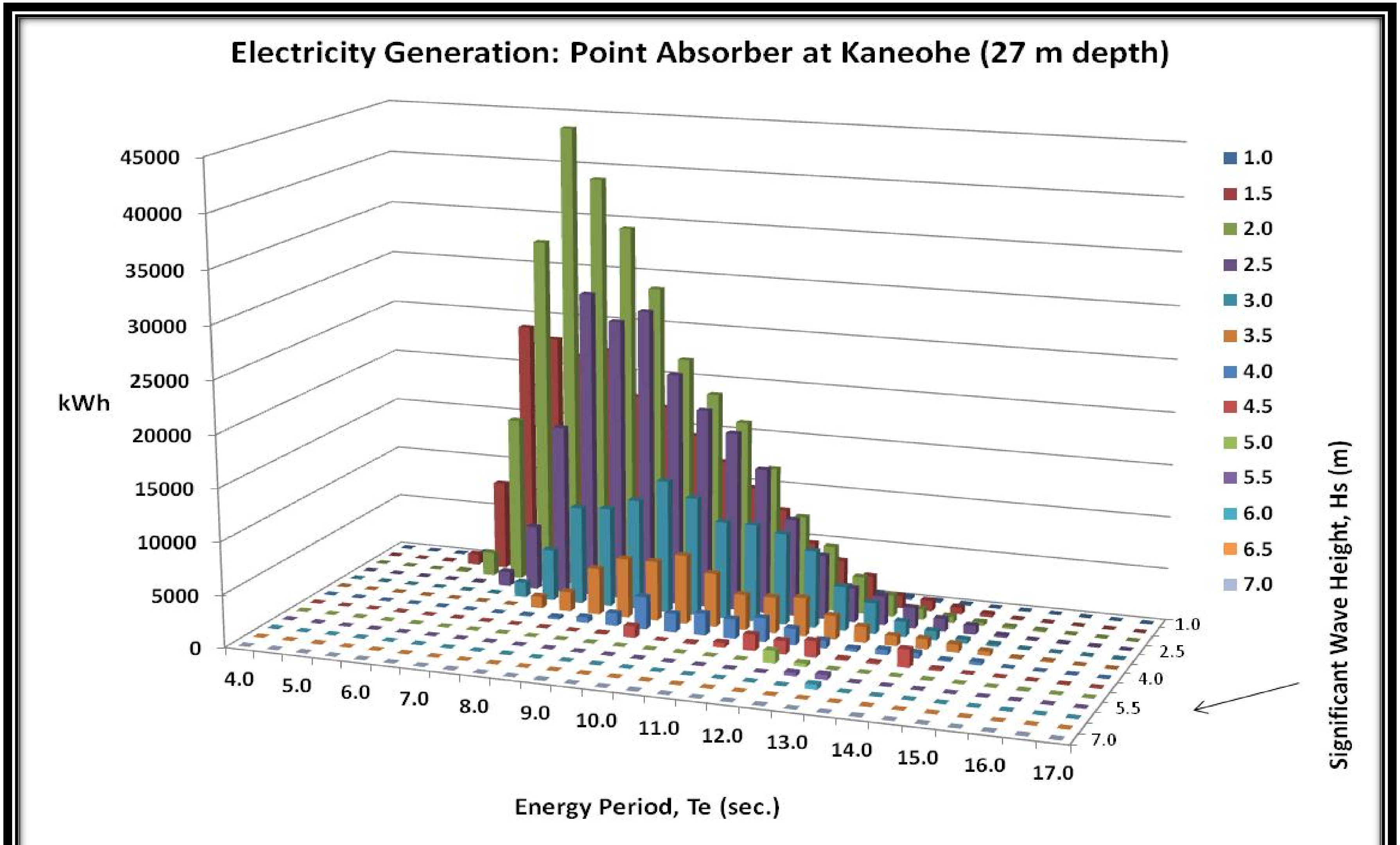
Wave Energy Conversion (WEC) Device Performance

Power Matrix x ***Wave Scatter*** *= Electricity Generation*



Wave Energy Conversion (WEC) Device Performance

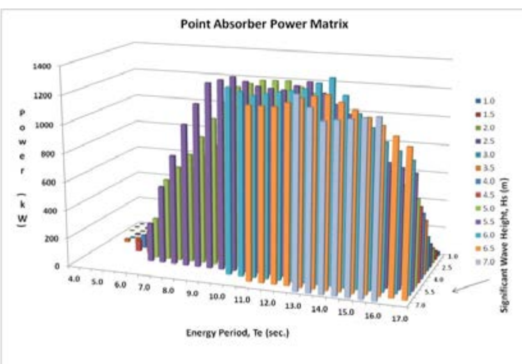
Power Matrix x Wave Scatter = Electricity Generation



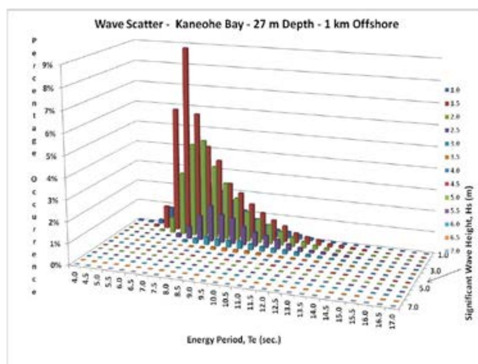
	"Name Plate"	Kaneohe, Oahu	Kilauea, Kauai	Pauwela, Maui	Kaneohe, Oahu
Wave Scatter Data (Year)		2009	2009	1990-2009	1990-2009
Site Depth		58 m	53 m	73 m	86 m
Site Wave Power Flux: Po		13.8 kW/m	21.6 kW/m	23.1 kW/m	12.1 kW/m
WEC Device		**Annual MWh:**	**Annual MWh:**	**Annual MWh:**	**Annual MWh:**
*** Point Absorber IEC/TS 62600-100 Annex A** www.iec.ch	1000 kW	1048 MWh **CF: 0.12**	1343 MWh **CF: 0.15**	1951 MWh **CF: 0.22**	1105 MWh **CF: 0.13**
*** Pelamis** www.pelamiswave.com	750 kW	826 MWh **CF: 0.13**	743 MWh **CF: 0.11**		
*** Wavestar C5** http://wavestarenergy.com	600 kW	2494 MWh **CF: 0.47** Curtail 4 days	2331 MWh **CF: 0.44** Curtail 22 days		

← Theoretical Resource

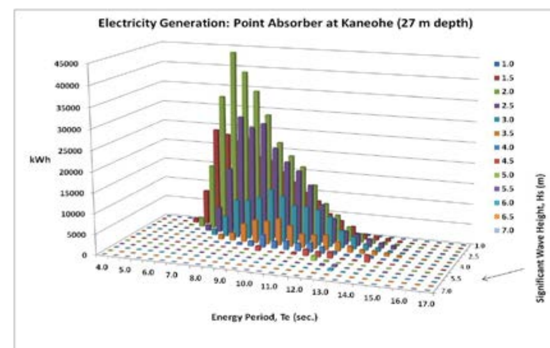
← Technical Resource



X



=



Wave Energy Conversion (WEC) Device Performance

Power Matrix x Wave Scatter = Electricity Generation

Electrical Generation with Hypothetical "1 MW" Point Absorber

Site	Wave Scatter	Annual Po (kW/m)	Annual MWh	Max hour Po (kW/m)
Pauwela (Maui) 73 m Depth	Hindcast (1990-2009) 3 km offshore	23	1,560 CF: 0.18	350
Grays Harbor (WN) 40 m Depth	NDBC (1987-2008) 9 km offshore	31	2,025 CF: 0.23	1160
Col. Rvr Bar (WN/OR) 135 m Depth	NDBC (1999-2008) 40 km offshore	40	2,630 CF: 0.30	1420
		Theoretical Resource	**Technical Resource**	**Survival**

Can your WEC device survive 1300 kW/m?

Capital Costs & LCOE ($/kWh)

Wave Energy Conversion (WEC) Devices

- Resource ample in numerous locations but equipment required to generate electricity requires one to two decades of diligent development to achieve full commercialization;
- Premature/unfair to lend validity to CC ($/kW) and LCOE ($/kWh) estimates;
- Their potential capacity factor (CF) < 0.5 similar to PV and WTGs $\rightarrow$ CC target defined.

Ocean Thermal Energy Conversion (OTEC)

- State of development such that under certain scenarios cost competitive baseload electricity could be produced, CF > 0.9

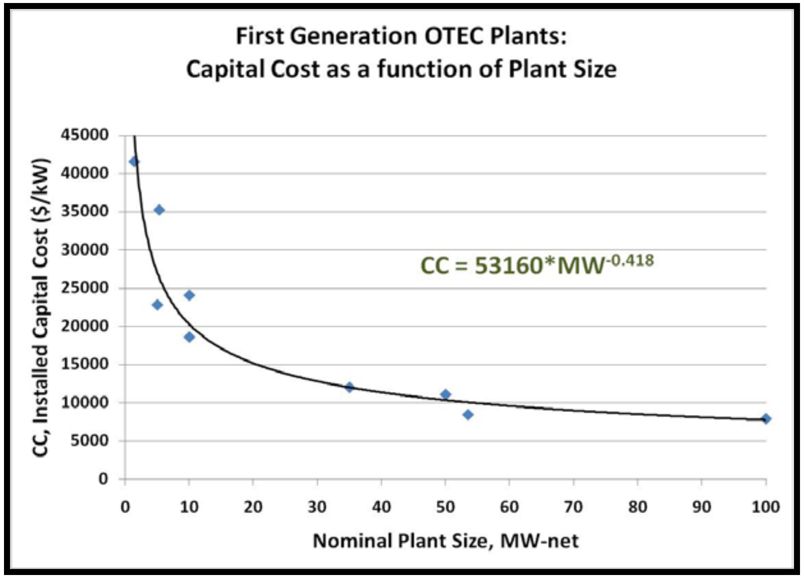
Capacity Factor

Annual Production (kWh) = Name Plate (kW) x 8760 hours x CF.

Case	Size	Cap. Fac.	CC	Loan (I/N)	*COE cc*	*COE omrr*	**COE**
			($/kW)	%/years	*$/kWh*	*$/kWh*	**$/kWh**
Future	*90 MW*	0.40	3,000	8/15	*0.1*	*0.070*	**0.17**
"		"	"	2.5/20	*0.055*	*0.077*	**0.13**
Future	*90 MW*	0.25	3,000	8/15	*0.16*	*0.112*	**0.27**
"		"	"	2.5/20	*0.088*	*0.123*	**0.21**
Future	*90 MW*	0.15	3,000	8/15	*0.267*	*0.187*	**0.45**
"		"	"	2.5/20	*0.147*	*0.206*	**0.35**
1st Gen.	750 kW	0.40	10,000	8/15	*0.333*	*0.233*	**0.57**
		"	"	2.5/20	*0.183*	*0.257*	**0.44**
1st Gen.	750 kW	0.25	10,000	8/15	*0.534*	*0.372*	**0.91**
		"	"	2.5/20	*0.293*	*0.411*	**0.70**
1st Gen.	750 kW	0.15	10,000	8/15	*0.891*	*0.623*	**1.51**
		"	"	2.5/20	*0.489*	*0.687*	**1.18**

Premature/unfair (or target) estimates of the LCOE ($/kWh) with Wave Energy Conversion Devices and Arrays

First Generation CC-OTEC Plants

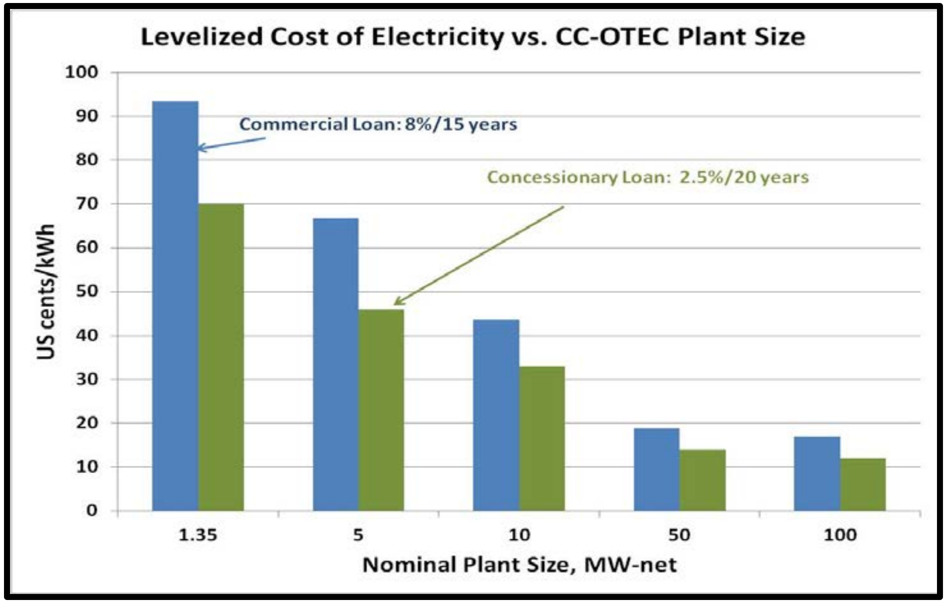


Capital Cost (CC) Estimates ($/kW)

LCOE ($/kWh) =

CC Amortization + Levelized OMR&R

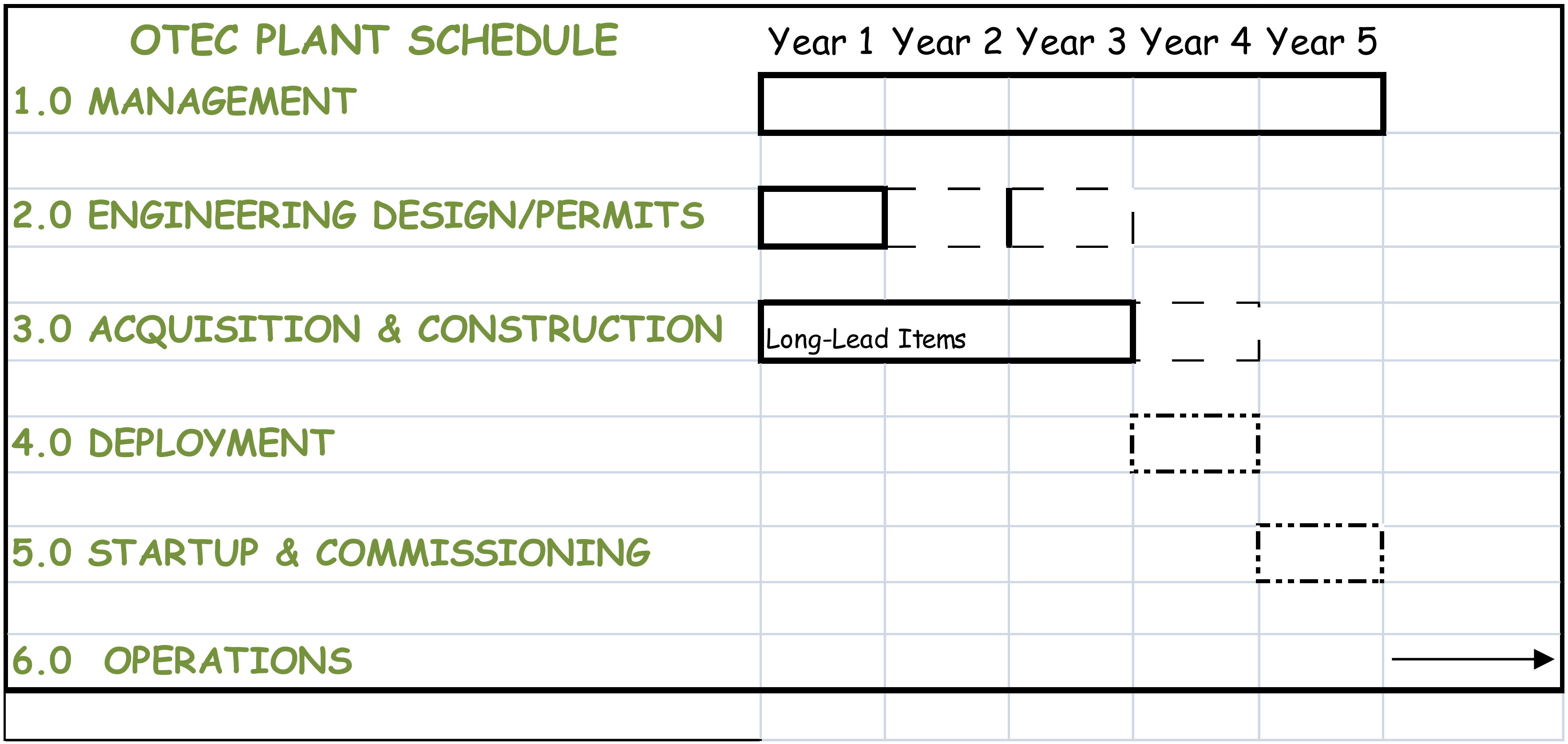
Annual Inflation @ 3%



What is the development time frame for a commercial OTEC system?

USA OTEC DEVELOPMENT		←	YEARS	→		
	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to ∞
Pre-Commercial Plant (> 5 MW)		Ops				
Electricity (Desal Water) Plants in Hawaii and USA Territories: ~ 20 x 100 MW Plants	Prelim Design		Ops	Ops	→	→
NH3/H2 Plantships Supplying all States				Prelim Design		Ops →

OTEC Pre-Commercial Plant Schedule



Potential World-Wide Market

How do we prepare for the post fossil fuels era?

Petroleum Fuels	< 50 Years
Natural Gas	< 120 years
Coal	< 100 years

- **Will need "Patient-Financing" for commercialization of Renewable Energy Technologies**

- **$50M - $200M funding for WEC Industry**
  over 5 - 10 years →
  $100s M to Billions world market by 2040

- **$200M - $500M funding for OTEC Industry**
  over 5 - 15 years →
  world market in Trillions by end of Century

Annex for Q&A only

Wave Resources: Conclusions & Recommendations

Theoretical Resource Availability	Equipment Siting Requirements	Additional Resource Information Needed	Equipment to Convert Resource into Electricity	Cradle-to-Grave Environmental Impact	Development Incentives	Overall Assessment	Overall Recommendation
Yes, in several nations but based on deepwater offshore data	- Water Depths < 80m - Coastal area: ~ 0.7 km^2 for 10 MW Array (comparable to offshore wind farm requirements)	(1) Commission Nearshore theoretical resource study using existing wind/wave numerical models. Requires bathymetry information; (2) Identify any wave measurements available to "calibrate" models.	Under early stages of development. Not currently available.	Not different from well established technologies and ocean installations with the exception of submarine power cable.	Implement fed-in-tariff for WEC Installations (intermittent resource). At current technology readiness level it is premature to estimate COE ($/kWh) but target should be comparable to PV and offshore wind.	(1) WEC devices will not be commercially available for installation for one to two decades; (2) Premature to estimate cost-of-electricity.	1) Obtain nearshore wave resource model for nations identified herein 2) Monitor progress in the development of WEC devices.

Ocean Thermal Resources: Conclusions & Recommendations

Theoretical Resource Availability	Equipment Siting Requirements	Additional Resource Information Needed	Equipment to Convert Resource into Electricity	Cradle-to-Grave Environmental Impact	Development Incentives	Overall Assessment	Overall Recommendation
Yes, widely available	- Water Depths >1000m - 100 MW plant housed in moored ship-shaped vessel the size of a standard super tanker. Submarine power cable connected to land.	(1) Identify sites close to electricity distribution lines; (2) Identify any ocean temp. data available (vertical distribution to 1000m).	Available off-the-shelve but capital intensive system	Not different from well established technologies and ocean installations with the exception of: (i) submarine power cable; and , (ii) seawater return to ocean (plume) below photic layer	- Implement multiple-year fed-in-tariff for OTEC Installations (baseload resource); - Loan guarantees; Target Tariff: > 0.25 $/kWh (> 50 MW plant) 0.50 $/kWh (10 MW plant)	(1) Need to implement pilot plant to obtain operational record required to secure financing; (2) Appropriately sized OTEC plants could be available for ~ 5 to 10 years.	1) Perform the tasks listed under “Additional Resource Information Needed”; 2) Monitor progress of pilot (pre-commercial) projects; and, implementation of small plants (< 10 MW).

Area: 100 MW Energy (Array) Farm

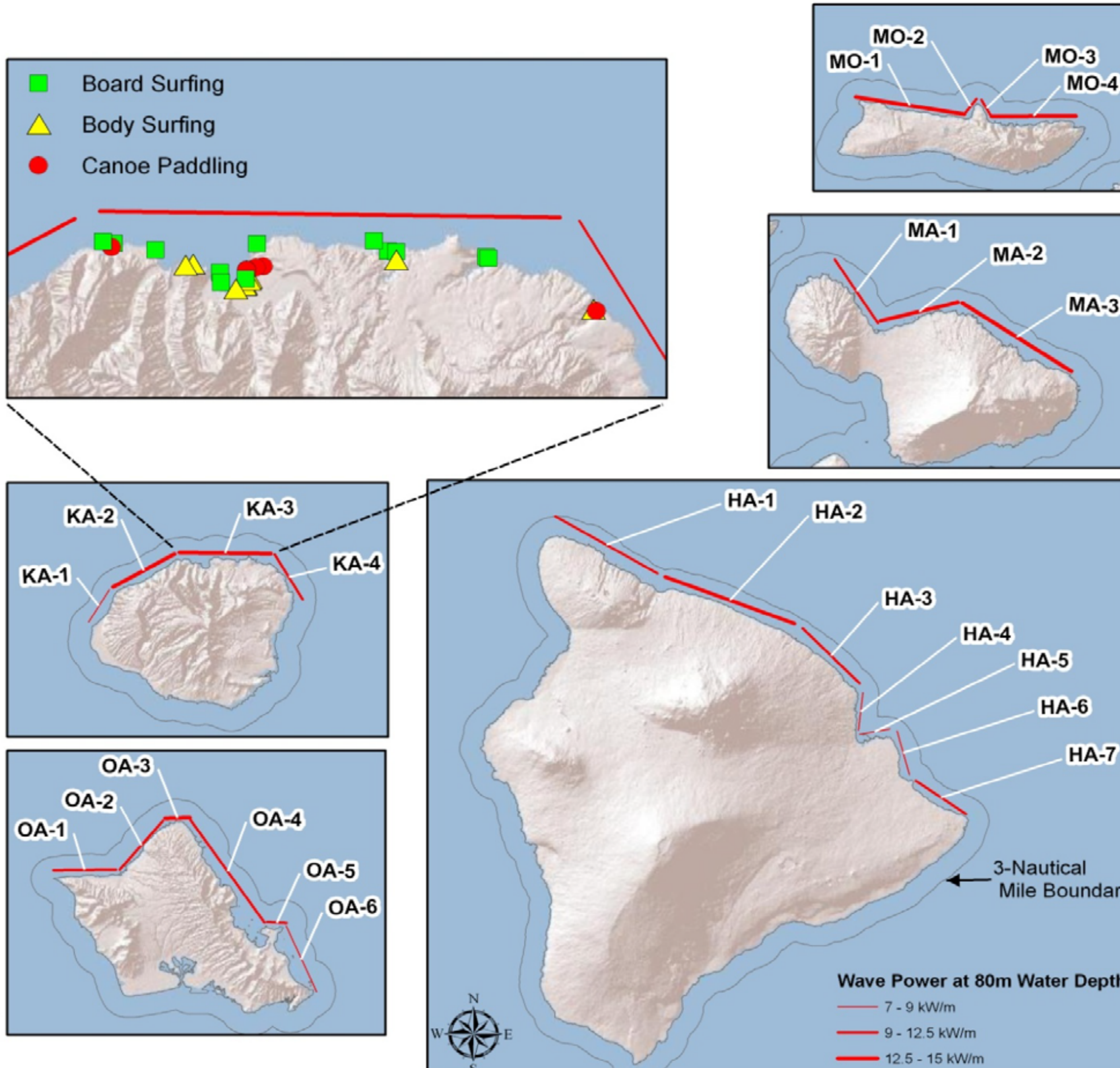
WECs: 11 km (6.7 miles) x 0.6 km (0.4 miles) (≤7 km^2);

{PV Farm ~ 2 km^2; and, Offshore Wind Farm ≤ 12 km^2}

	CF: % of 8760 hrs at Name Plate
SOLAR- PV	
4 kWh/m^2day	**18%**
5 kWh/m^2day	**20%**
WIND	
6 m/s Annual Average	**18%**
8 m/s	**33%**
10 m/s	**53%**
WAVE	
This report	**12% to 47%**
"EPRI West Coast"	**22% to 32%**

Figure #. Average Wave Power (kW/m) Along Selected Coastal Segments and Potential Constraints

	Coastal Segment	5 m Water Depth (kW/m)	80 m Water Depth (kW/m)
KAUAI	KA-1	6	9
	KA-2	10	13
	KA-3	12	15
	KA-4	9	12
OAHU	OA-1	10	11
	OA-2	8	12
	OA-3	12	14.5
	OA-4	8	11
	OA-5	10	12
	OA-6	7	9
MOLOKAI	MO-1	12	14
	MO-2	8	10.5
	MO-3	8	11
	MO-4	12	14
MAUI	MA-1	9	12
	MA-2	10.5	13.5
	MA-3	10.5	13.5
HAWAII	HA-1	9	10
	HA-2	11	13
	HA-3	10	12.5
	HA-4	5	7
	HA-5	6.5	8
	HA-6	6	8
	HA-7	10	11



Data Sources:
Hagerman (1992)
Kauai Coastal Resource Atlas, USACE (1984)

Hawaii Electricity Demand: Contribution Potential

Island	Wave Farm	Challenge	OTEC	Challenge
Oahu	< 17%	Siting: *requires all shoreline segments;* Storage: *intermittent resource*	>> 100%	No prototype operational data
Maui	< 75%	"	>> 100%	"
Hawaii	< 150%	"	>> 100%	"
Kauai	< 300%	Siting: *requires 30% shoreline segments;* Storage: *intermittent resource*	>> 100%	"
Molokai	< 2000%	Storage: *intermittent resource*	>> 100%	"