Ocean Thermal Energy Conversion (OTEC) : Electricity and Desalinated Water Production

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Puerto Rico Ocean Thermal Resource: Truisms

- OTEC plants <u>could supply all</u> the electricity and potable water consumed in Puerto Rico, {but at what cost?}

- Only <u>indigenous renewable energy resource</u> that can provide a high degree of energy security to the State and in addition minimize green house gas emissions;

Generalities

Visionary Perspective: *Don Quijote de la Mancha*

On annual basis:

- Solar energy absorbed by oceans is $\approx$ 4000 x human consumption;
- < 1 % Extraction would satisfy all.

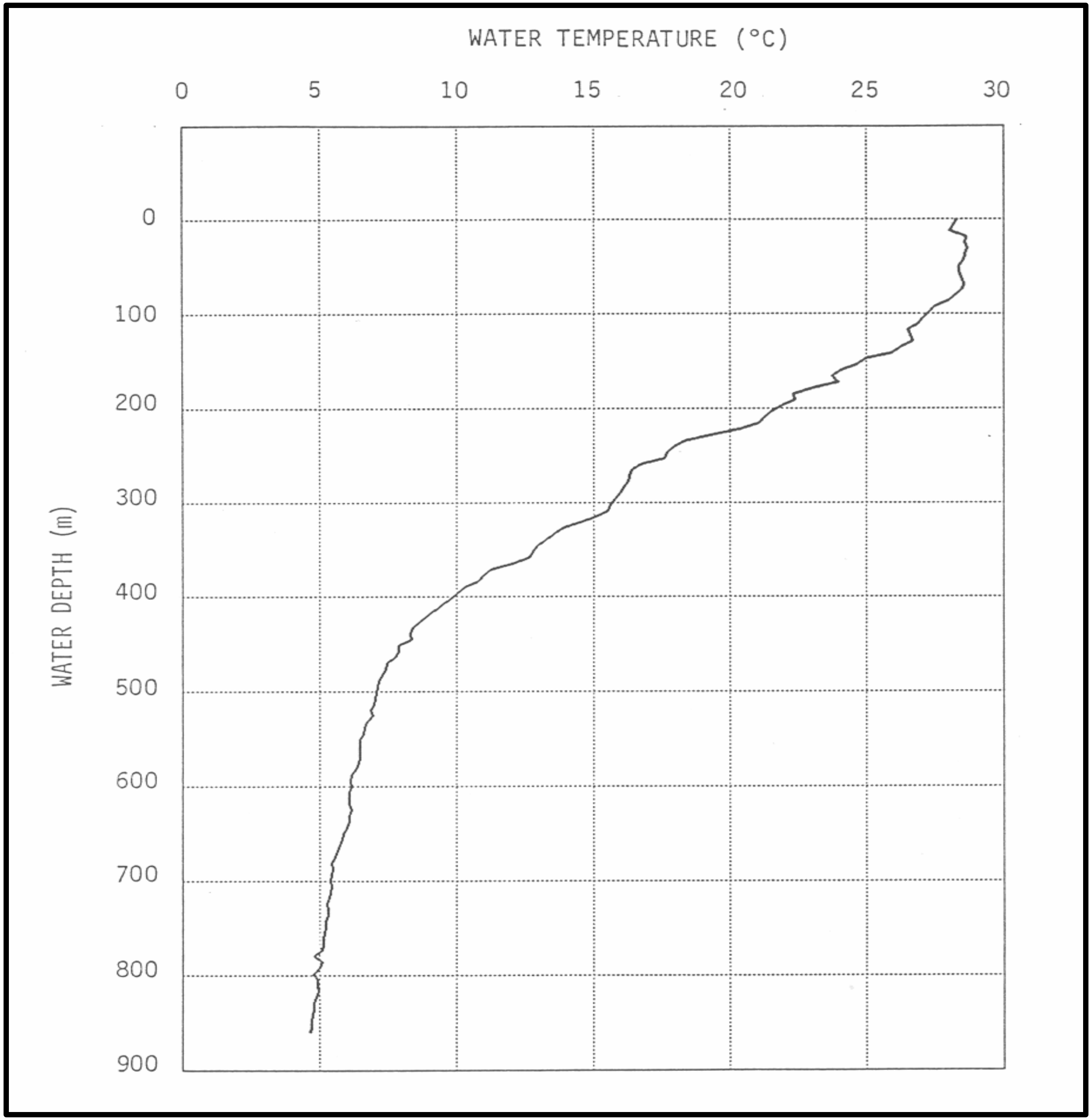
[OTEC: thermal $\rightarrow$ electric conversion $\approx$ 3 %]

Engineering Perspective: *Sancho Panza*

- Ocean's vertical temperature distribution ?

heat source and heat sink required to operate heat engine

i.e., two layers with $\Delta T \approx 22$ °C in equatorial waters...


WATER TEMPERATURE (°C)
0
5
10
15
20
25
30
WATER DEPTH (m)
0
100
200
300
400
500
600
700
800
900

The Concept

OTEC Concept

Ocean Thermal Resource (fuel) ?

- Cold Water: @1000 m depth

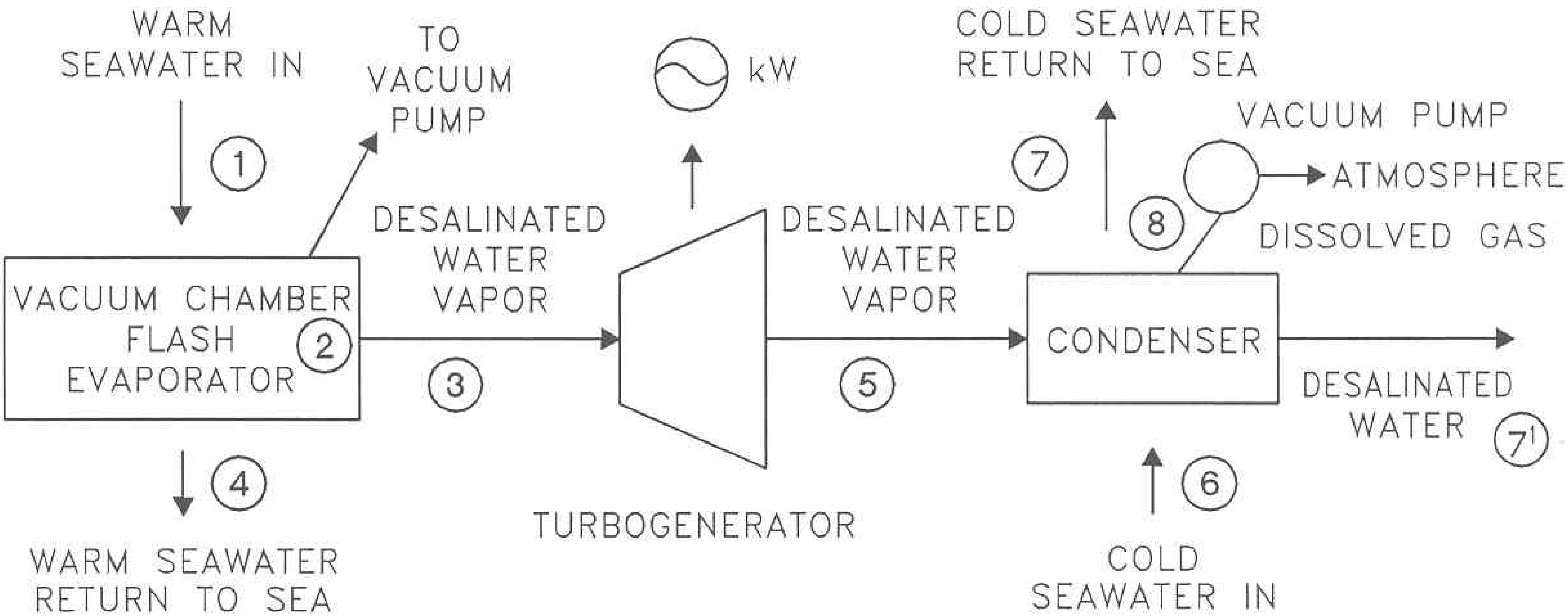
  4 °C to 5 °C

- Warm Water: Tropical seas at "surface"

  24 °C to 30 °C

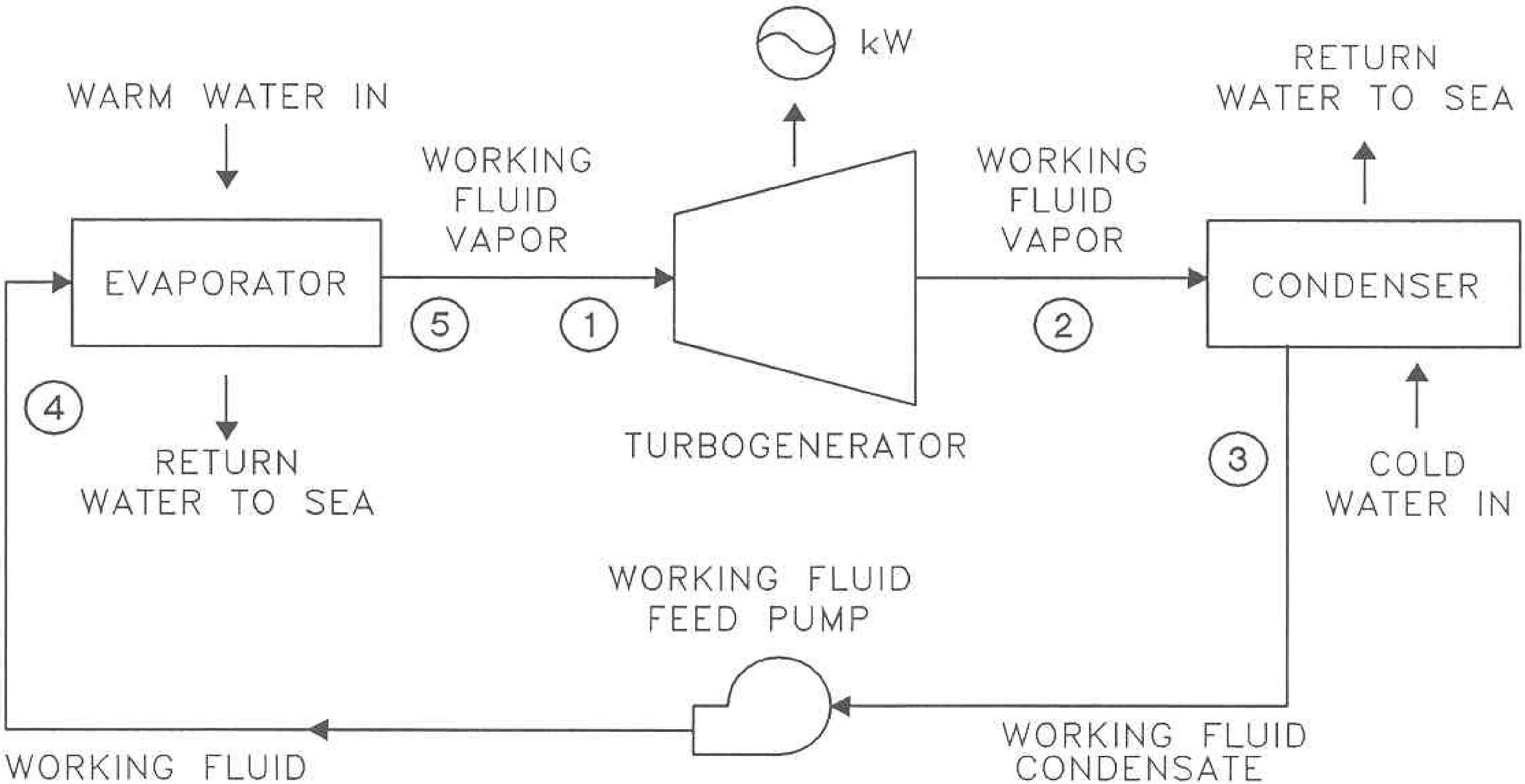
Open Cycle OTEC

Surface seawater is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The open-cycle can, therefore, be configured to also produce fresh water:


WARM
SEAWATER IN
TO
VACUUM
PUMP
kW
COLD SEAWATER
RETURN TO SEA
VACUUM PUMP
1
7
ATMOSPHERE
DESALINATED
WATER
VAPOR
DESALINATED
WATER
VAPOR
8
DISSOLVED GAS
VACUUM CHAMBER
FLASH
EVAPORATOR
2
CONDENSER
3
5
DESALINATED
WATER
7'
4
6
TURBOGENERATOR
WARM SEAWATER
RETURN TO SEA
COLD
SEAWATER IN

Closed Cycle OTEC

Warm surface seawater and cold deep seawater are used to vaporize and condense a working fluid, such as ammonia, which drives a turbine-generator in a closed loop producing electricity:



kW
WARM WATER IN
RETURN WATER TO SEA
WORKING FLUID VAPOR
WORKING FLUID VAPOR
EVAPORATOR
CONDENSER
5
1
2
4
3
TURBOGENERATOR
RETURN WATER TO SEA
COLD WATER IN
WORKING FLUID FEED PUMP
WORKING FLUID
WORKING FLUID CONDENSATE

Thermal Resource

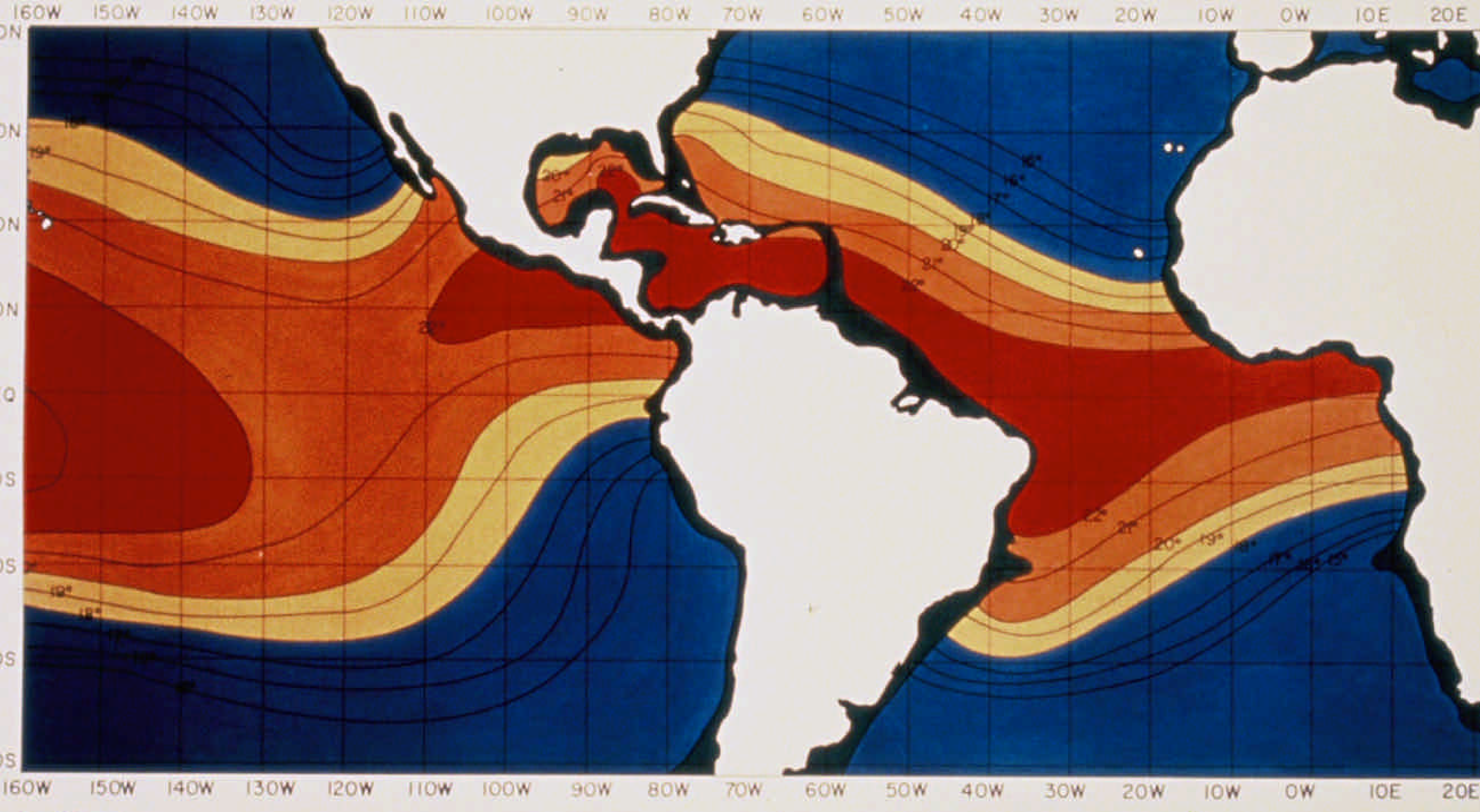
Temperature Difference between Surface Water and 1,000 m Water (want > 20 °C) :

Yellow	18 to 20 °C
Orange	20 to 22 °C
Red	22 to 24 °C

LARGE SCALE DISTRIBUTION OF

OTEC THERMAL RESOURCE

ΔT(°C) BETWEEN SURFACE AND 1000 METER DEPTH



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- Economics & COE ($/kWh)
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What is known about OTEC Technology?

- <u>Continuous</u> production of electricity and desalinated water has been demonstrated with experimental plants:


MiniOTEC
(1979)
50 kW CC-OTEC
MINI OTEC

Nauru **(1982)**

100 kW CC-OTEC

50 kW CC-OTEC (NH_3) Test Apparatus

(Vega: 1999)

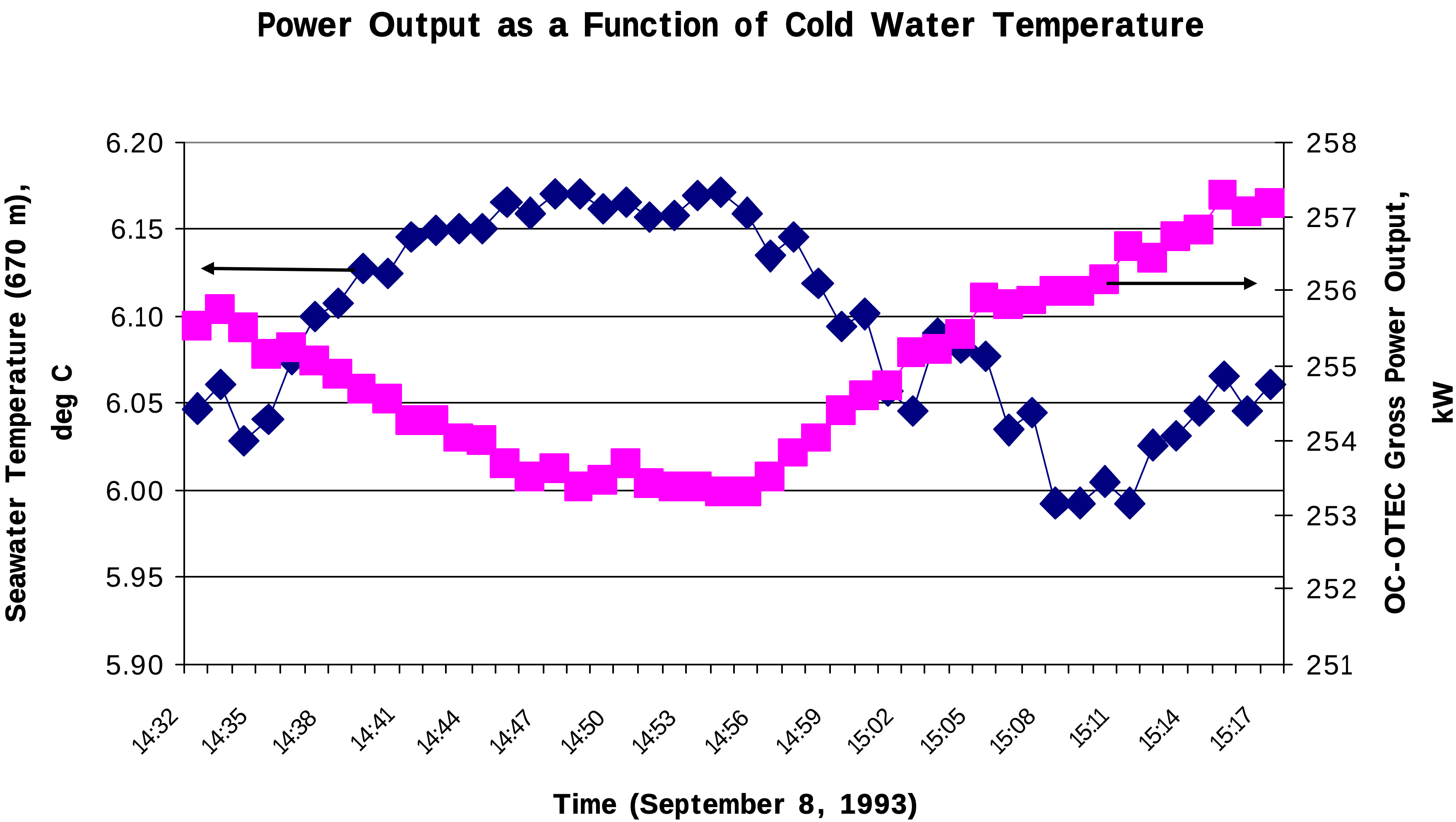
210 kW OC-OTEC Experimental Plant

(Vega: 1993-1998)

Desalinated Water Production (Vega:'94-'98)

OTEC Power Output as Function of Control Parameters

- Open Cycle Control Parameters: Seawater Mass Flow Rates; *Seawater Temperatures* & Vacuum Compressor Inlet Pressure
- Closed Cycle Control Parameters: Seawater Mass Flow Rates; *Seawater Temperatures* ; NH_3 Mass Flow Rate & Recirculation/Feed Flow Ratio


Power Output as a Function of Cold Water Temperature
Seawater Temperature (670 m), deg C
6.20
6.15
6.10
6.05
6.00
5.95
5.90
258
257
256
255
254
253
252
251
OC-OTEC Gross Power Output, kW
14:32
14:35
14:38
14:41
14:44
14:47
14:50
14:53
14:56
14:59
15:02
15:05
15:08
15:11
15:14
15:17
Time (September 8, 1993)

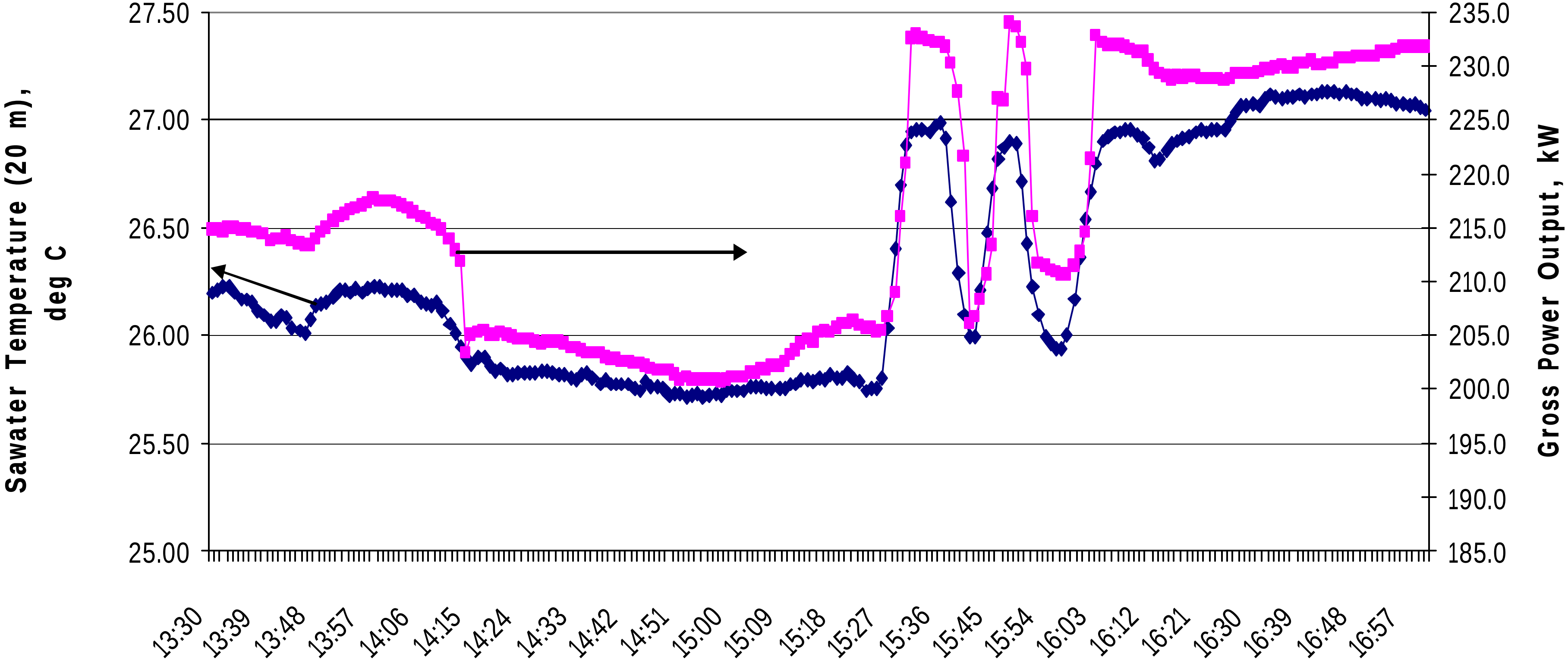
OC-OTEC Power Output vs Cold Water Temperature

1-minute Averages of 1-sec samples show:

Cold Seawater Temperature Oscillation as Signature of Internal Waves

(λ ~3,500m; P ~ 60 minutes; H ~ 50 m)

OC-OTEC Power Output as a Function of Warm Water Temperature

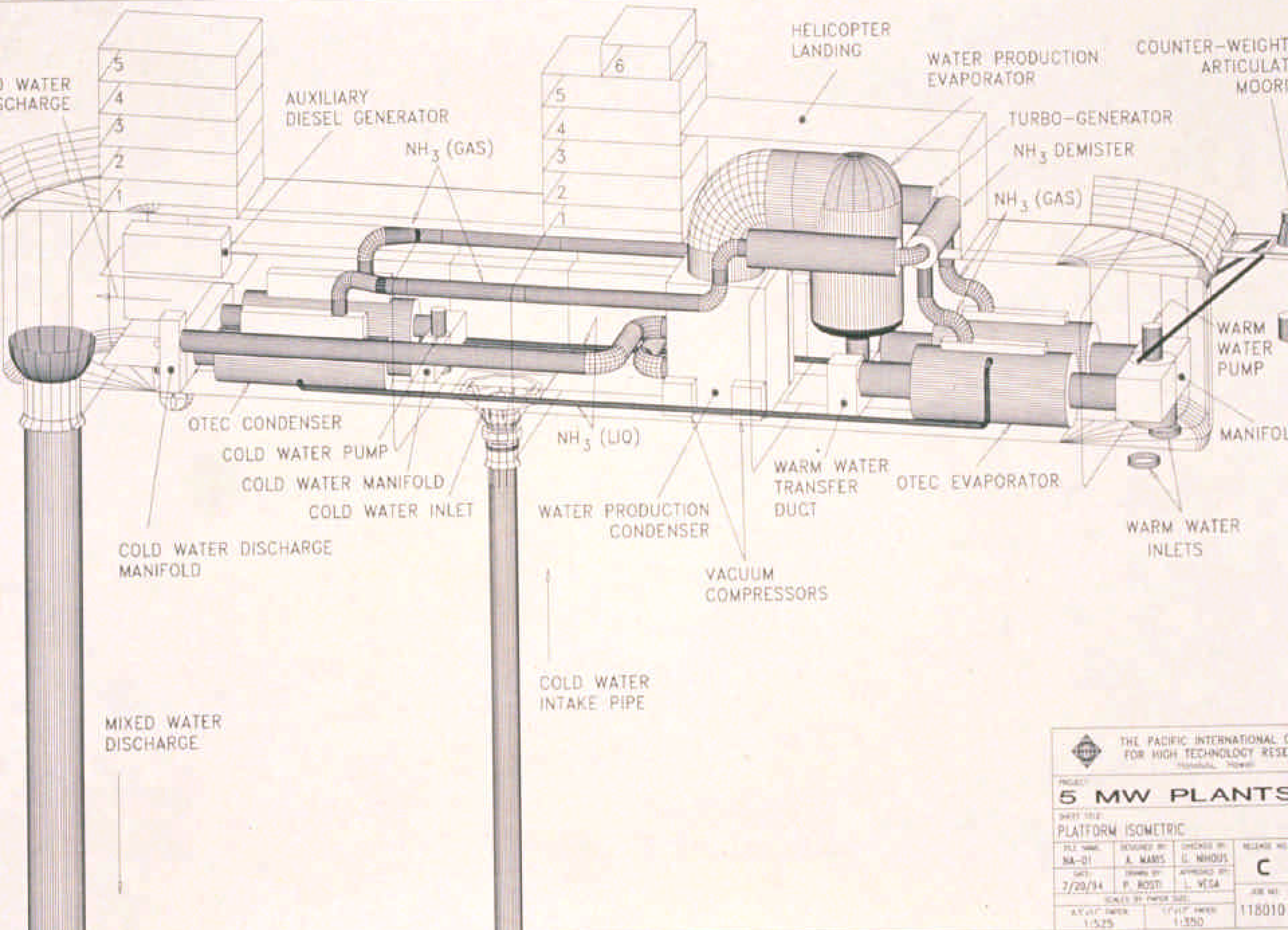


OC-OTEC Power Output vs Warm Water Temperature

1-minute Averages of 1-sec samples show:

Surface Seawater Temperature Variation as Signature of Warmer Water Intrusion driven by Ocean Gyre shed from Alenuihaha Channel between Maui and Hawaii (Big Island)

5 MW Pre-Commercial Plant


HELICOPTER LANDING
WATER PRODUCTION EVAPORATOR
COUNTER-WEIGHT
AUXILIARY DIESEL GENERATOR
TURBO-GENERATOR
NH_3 (GAS)
NH_3 DEMISTER
NH_3 (GAS)
WARM WATER PUMP
OTEC CONDENSER
COLD WATER PUMP
COLD WATER MANIFOLD
COLD WATER INLET
NH_3 (LIQ)
WATER PRODUCTION CONDENSER
WARM WATER TRANSFER DUCT
OTEC EVAPORATOR
WARM WATER INLETS
COLD WATER DISCHARGE MANIFOLD
VACUUM COMPRESSORS
COLD WATER INTAKE PIPE
MIXED WATER DISCHARGE
5 MW PLANTS
PLATFORM ISOMETRIC
NA-01
7/20/94
C
118010

OTEC Plant Crew

- 20-people Staff for 24/7 Operations:

  Minimal:

  Technicians: 12 (covers all shifts)

  Engineering & Admin: 5

? Independent of Plant Size

Lessons Learned

- Life-Cycle Design
- Constructability
- System Integration

Lessons Learned

Life-Cycle Design

e.g., locating a component in the water column might yield higher efficiencies but result in elaborate maintenance requirements and higher operational costs

Lessons Learned

Constructability

Can equipment be manufactured using commercially available practices and in existing factories?

Lessons Learned

System Integration

In addition to power block (HXs & T-G), OTEC includes seawater subsystems; dynamic positioning subsystems; and, submarine power cable

What is known about OTEC Economics ?

- Economically competitive under certain “scenarios”

(defined by fuel-and-water-costs) :

Cost of Electricity Production

COE ($/kWh) = CC + OMR&R + Profit

+ Fuel *(for OTEC zero)*

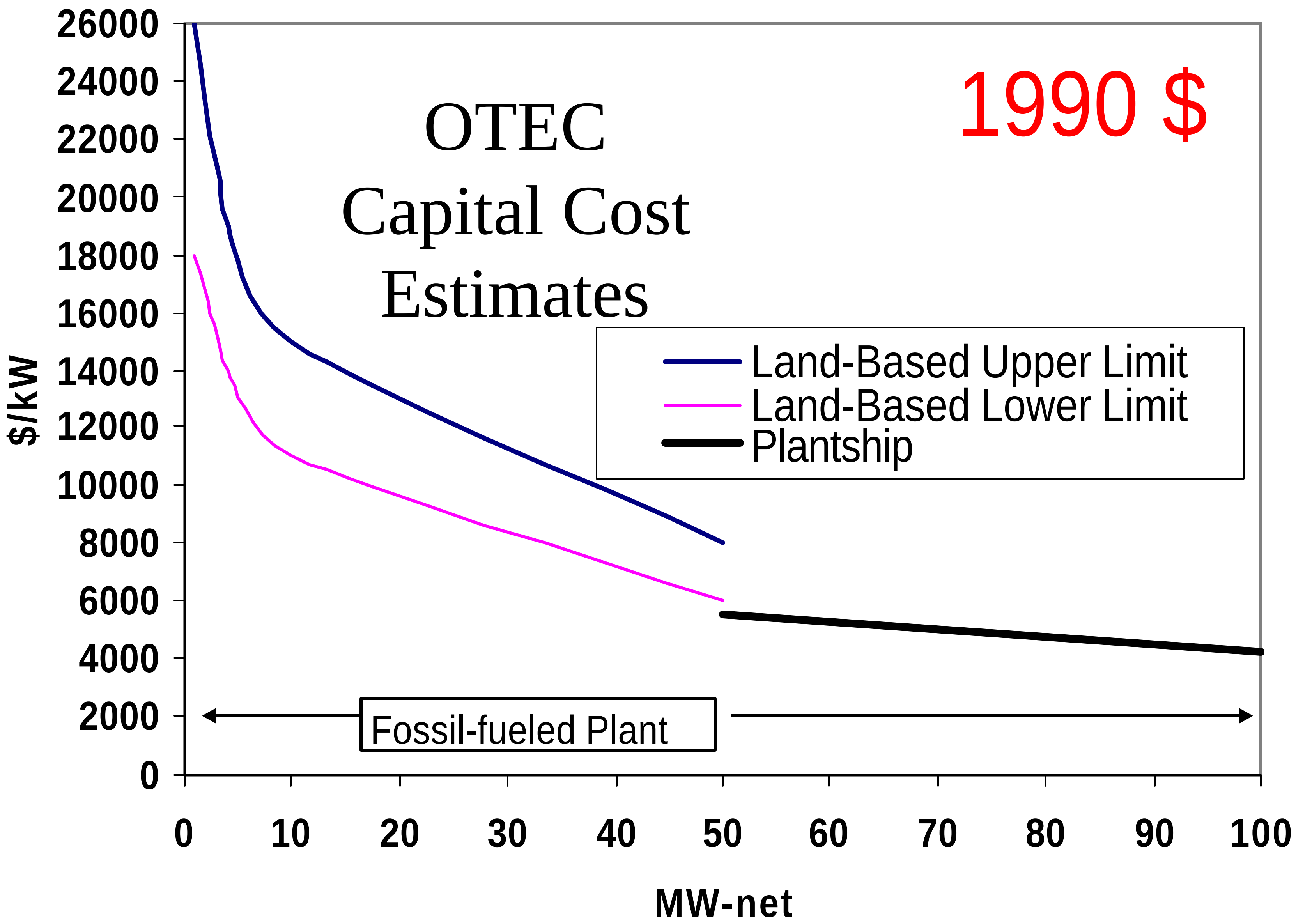
- Environmental Credit

CC = Capital Cost Amortization

(N.B. much higher for OTEC)

OMR&R = Operations + Maintenance + Repair + Replacement

Tariff = COE - Subsidy



1990 $
OTEC
Capital Cost
Estimates
Land-Based Upper Limit
Land-Based Lower Limit
Plantship
Fossil-fueled Plant
$/kW
26000
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
80
90
100
MW-net

Please Beware!!

Economy of Scale 10 vs. 100 MW ?

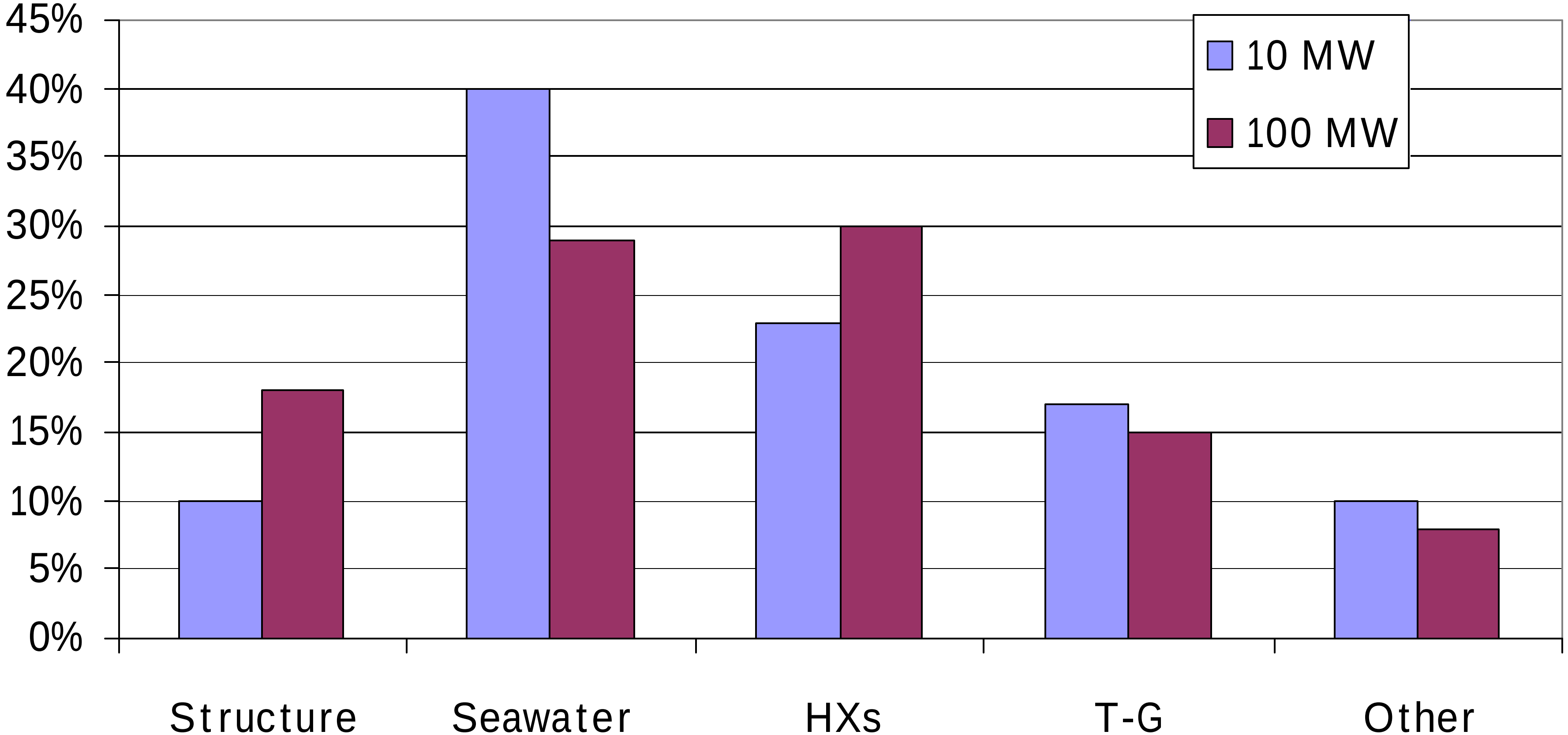
- Power Block Cost of 100 MW plant is

  ~ 10 x 10 MW
- Seawater Subsystems & At-Sea Deployment of 100 MW is

  < 10 x 10 MW
- Staffing requirements constant

  100 MW = 10 MW

OTEC Capital Cost: Plant Size Dependency



Nominal Size, MW	TYPE (After Eng. Dev.)	Scenario (by ~ 10th Plant)	Potential Sites
1	Land-Based OC-OTEC with 2nd Stage for Additional Water Production.	**Diesel: $45/barrel Water: $1.6/m^3**	Present Situation in Some Small Island States.
10	Same as Above.	**Fuel Oil: $30/barrel Water: $0.9/ m^3**	U.S. Pacific Insular Areas and other Island Nations.
50	Land-Based Hybrid CC-OTEC with 2nd Stage.	**$50/barrel $0.4/ m^3 or $30/barrel $0.8/ m^3**	Hawaii, **Puerto Rico** If fuel or water cost doubles.
50	Land-Based CC-OTEC	**$40/barrel**	Same as Above.
100	CC-OTEC Plantship	**$20/barrel**	Numerous sites

Fuel and Water Costs Required for Competitiveness (1990)

Cost of Electricity Production

Offshore Distance, km	Capital Cost, $/kW 10th Plant	COE, $/kWh 10%/20-years
10	4,200	0.07
50	5,000	0.08
100	6,000	0.10
200	8,100	0.13
300	10,200	0.17
400	12,300	0.22

2nd Generation 100 MW CC-OTEC

(1992 Analysis/Projection)

Updated Assessment ('07)

- For example, Avoided Energy Cost in Hawaii ~ 0.20 $/kWh [was < 0.06 $/kWh in 90's]
- Petroleum resources (IEA, API, USGS) available to meet world demand for the next 30-50 years; however, diminishing resources ? price increases
- This situation justifies re-evaluating OTEC for the production of electricity

Global Oil Resources

- Consumption (IEA, API): ~ 80 MBPD (million barrels per day)

  By 2030 ~ 1.5 X;

- Resource (IEA, USGS, API):

  ~ 1.4 Trillion BBLs (others say 1 to 3)

  e.g., Saudi Arabia "claimed and claims" 265 Billion BBLs (presently produces 11 MBPD)

- 70% of Barrel used transporting people and goods

Global Oil Resources

- Consensus:
  - 30 to 50 years until oil gone
  - Diminishing resources ? Price Increases
- Presently, H_2 produced with OTEC electricity is equivalent to ~ 8 x price of oil

? Would it be wise to begin to consider H_2 production onboard OTEC plantships deployed along Equator?

OTEC Commercialization?

Pro:

- Less environmental impact than conventional power plants;
- As long as the sun heats the oceans, the fuel for OTEC is unlimited and free.

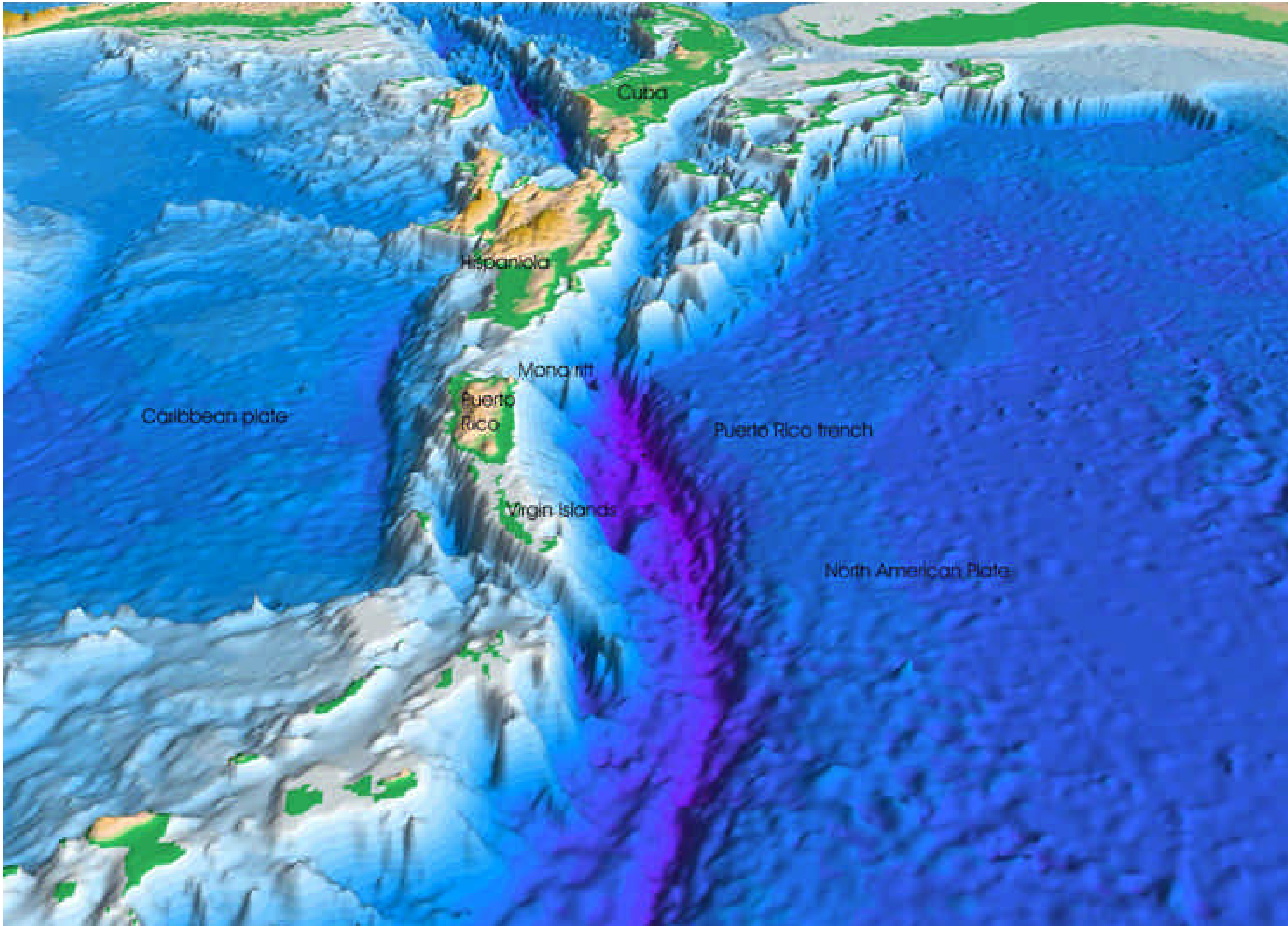
Con:

- No operational record with <u>large</u> size plant

What Next for OTEC?

<u>Realistic Financing</u>

Based on detailed cost estimates not wishful dreaming

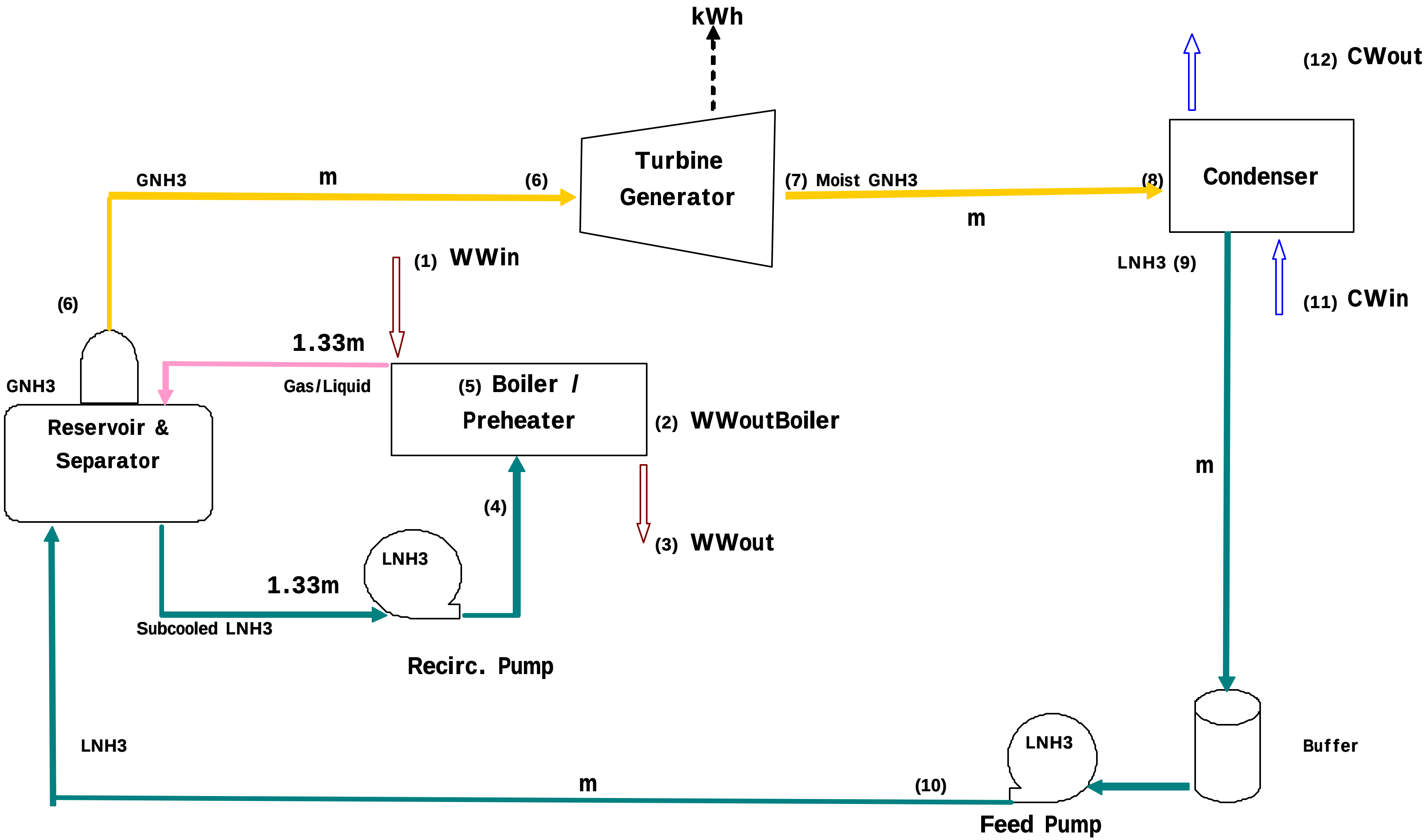

Cuba
Hispaniola
Mona rift
Puerto
Rico
Caribbean plate
Puerto Rico trench
Virgin Islands
North American Plate

Punta Tunas

- 1,000 m Depth 3,000 m Offshore
- Surface Water Temperature:

  27.7 ± 1.7 °C
- Deep Ocean (1,000 m) Water:

  5.4 ± 0.3 °C
- Design for ΔT : 22 °C (27.5/5.5)



m: mass flowrate of NH3, kg/s

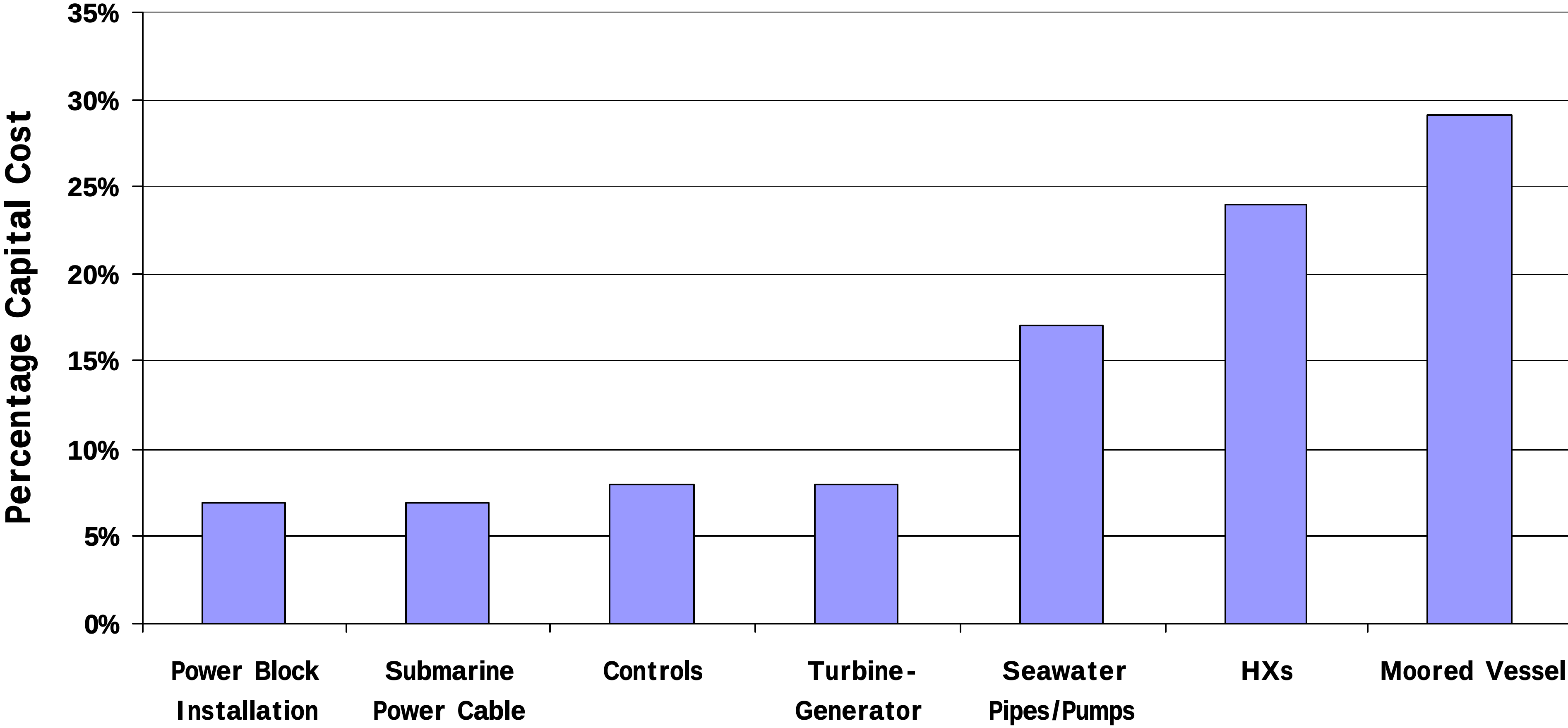
( ): state points

OTEC Process Flow Diagram

OTEC Capital Cost: 75 to 100 MW

Floating Vessel	25%
Mooring	4%
Submarine Power Cable	7% (10 km)
Seawater Pipes & Pumps	17%
Turbine-Generator	8%
Heat Exchangers	24%
All Controls (electrical/NH3/Cl2)	8%
Install Mech/Electr	7%

75 MW OTEC
(10 km offshore)



Electricity Cost ($/kWh): 75 MW

	1st Generation	1st Generation	Later Generations
Financing:	7.75%/ 10-years	idem/ 15-years	idem/ 10-years
CC:	0.144	0.112	0.101
OMR&R: (3% Annual Inflation)	0.023	0.024	0.023
Total:	0.166	0.136	0.123
"Avoided" Cost Equivalent:	*70 $/bbl* *[accounting for capital cost but no tax credit]*	*55 $/bbl*	*42 $/bbl*

Commercialization (Puerto Rico)

- Puerto Rico could use OTEC to Generate 100% of Electricity Presently Consumed;

- Commercial-size ≈ 75-100 MW floater - C.O.E competitive with ~ $60 per barrel Oil fired Generators. Later units competitive with ~$40 barrel

Development Barriers
(Puerto Rico)

Cost Issues: Cost Effective for Size ≈ 75 - 100 MW

Tech. Issues: Would be 1st Generation Commercial Size Plant

Enviro. Issues: Relatively Minimal

Political Issues: Need broad based bi-partisan support

Other Applications: AC

Cold deep water as the chiller fluid in air conditioning (AC) systems: load can be met using 1/10 of the energy required for conventional systems and with an investment payback period estimated at 3 to 4 years.

Energy Carriers

OTEC energy could be transported via electrical, chemical, thermal and electrochemical carriers:

Presently, *all yield costs higher than those estimated for the submarine power cable* *(< 400 km offshore).*

EXTERNALITIES

- What are external costs of energy production and consumption?
- In USA equivalent to adding \$85 to \$327 to oil barrel
- USA to safeguard overseas oil supplies → add ~ \$23 to barrel *(before Iraq)*

Final Thoughts:

Accounting for externalities will facilitate development and expand applicability of OTEC;

? Presently, can use OTEC plantships to transmit the electricity (and water) to land via submarine power cables (and flexible pipelines).

Annex

US Navy Small Island Installations

- Kwajalein Atoll (Marshall Islands)

Current (May'05-June'06)

~ 10 MW Capacity (diesel gensets)

COE ($/kWh) : [0.16 + 0.05] = 0.21

[fuel + OMR&R]

10 MW OTEC

Levelized COE ~ 0.30 $/kWh

US Navy Small Island Installations

- Situation similar in Diego Garcia (Indian Ocean Island)
- USN willing to issue Power-Purchase-Agreement if COE reduced by at least 10% (~ 0.9 x 0.21 = 0.19 $/kWh)
- <u>Can not do</u> with ~ 10 MW OTEC