MAKAI OCEAN ENGINEERING

OTEC in Hawaii and Beyond

MARES TA Webinar Series

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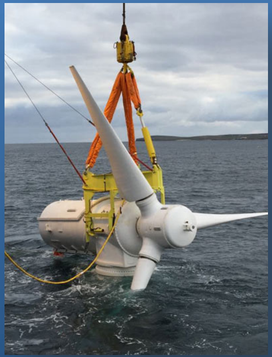
Overview

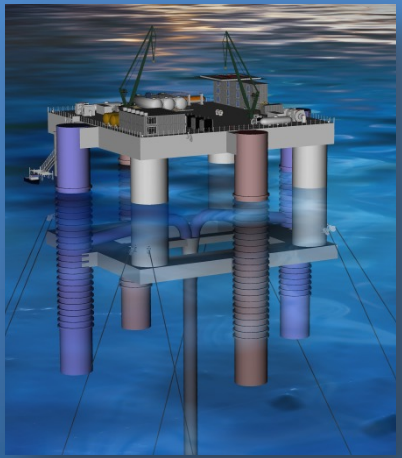
- Ocean Energy and Deep Water Technologies
- Sea Water Air Conditioning
- Ocean Thermal Energy Conversion
  - Resource
  - History
  - Developments
  - Costs and Challenges
- Grazing Opportunity and the Hydrogen Economy
- Ammonia as an Intermediary
- Conclusions and Next Steps

Ocean Energy and Deep Water Technologies

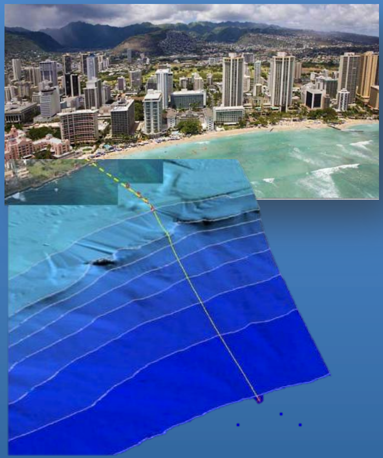
Wave



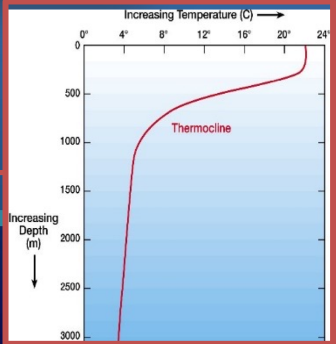
Tidal



OTEC



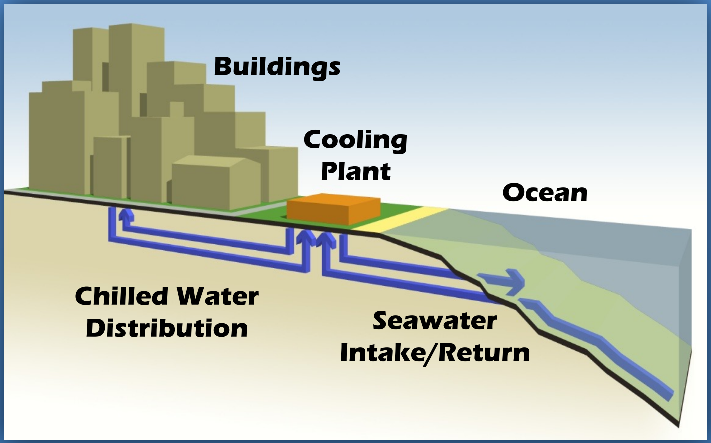
SWAC

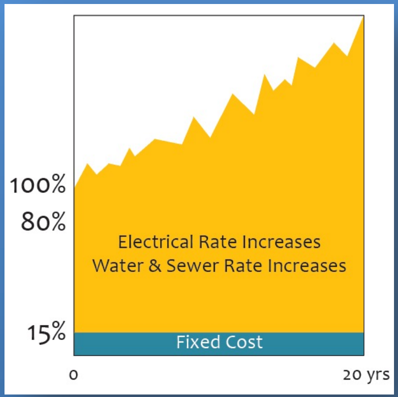


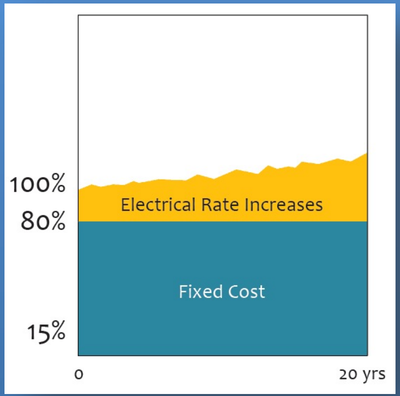
Floating Wind

Fixed Wind

SWAC: SeaWater Air Conditioning

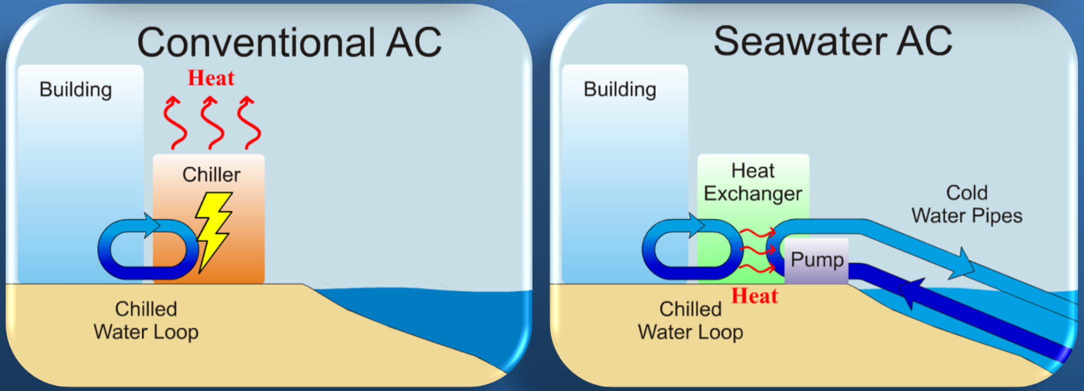




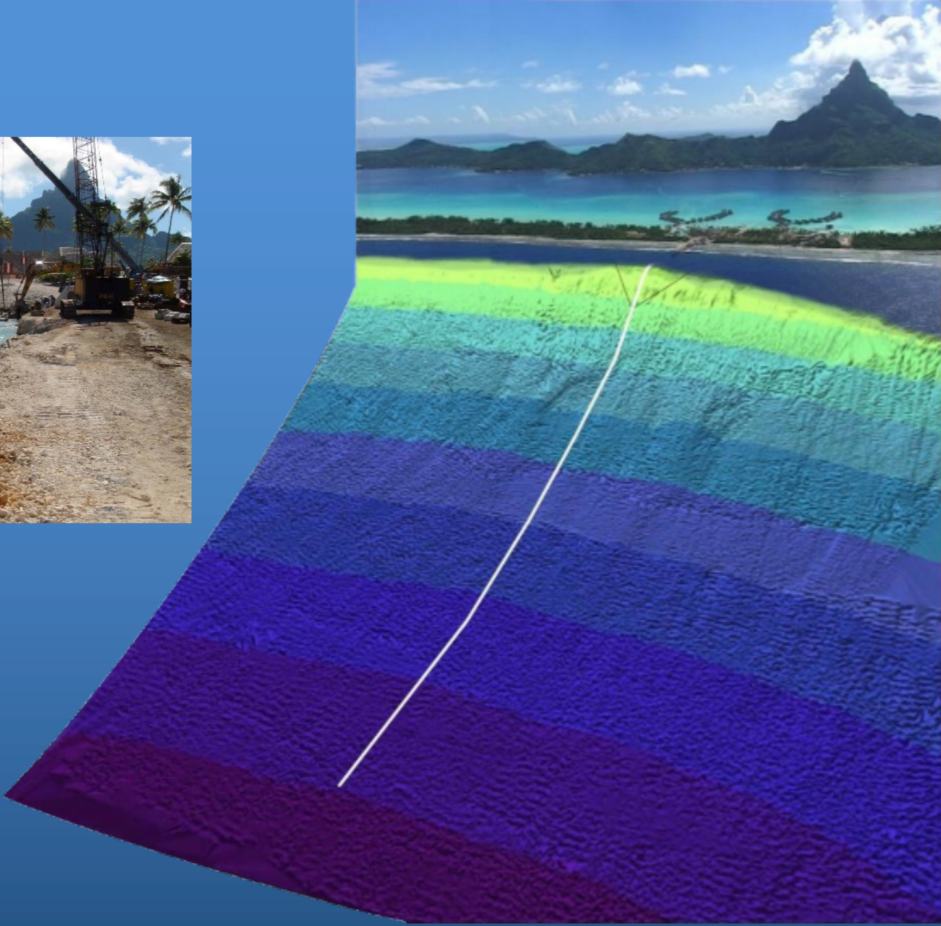


Main Components:

- Offshore pipes
- Pumps
- Heat exchangers
- Chilled water loops



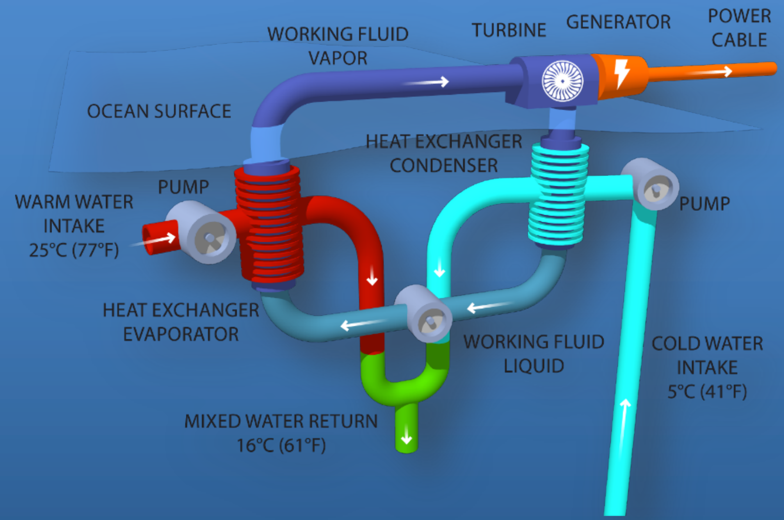
SWAC: Bora Bora



- 900m deep intake
- 40m deep discharge
- 450 Tons AC
- 1200 gpm
- 2.3 km long
- Pumps Onshore

OTEC: Ocean Thermal Energy Conversion

- In 1881 the French scientist D'Arsonval proposed the concept of Ocean Thermal Energy Conversion (OTEC)
- The OTEC system generates electricity via a heat cycle exploiting the temperature difference between a hot source (surface ocean water) and a cold sink (deep ocean water).
- Most commonly, OTEC utilizes a Rankine cycle, where the warm tropical ocean surface water is used to vaporize pressurized ammonia through a heat exchanger (evaporator) and then using the resulting vapor to drive a turbine generator.



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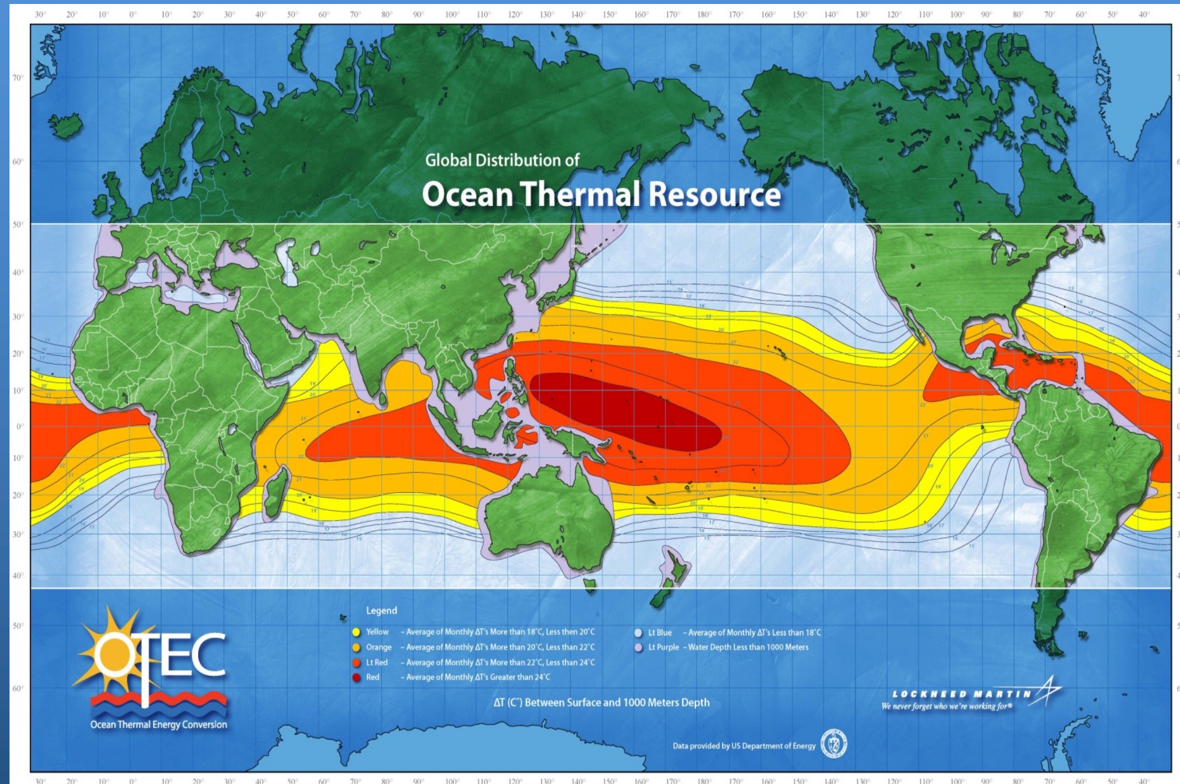
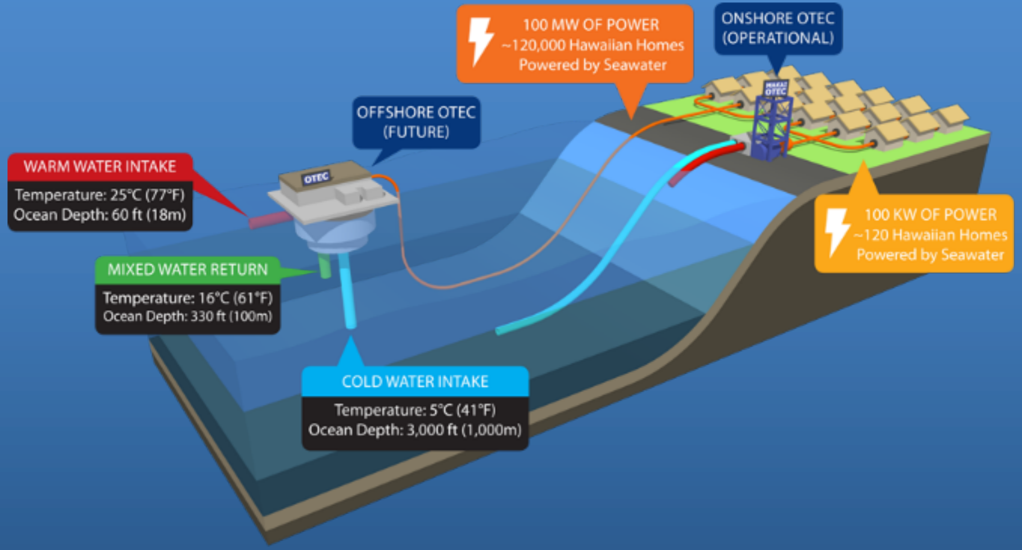
OTEC: The Resource

- ✓ **Large Renewable Energy Source**
  - At least 3-5 Terawatts*
- ✓ **Base Load Power**
  - Available 24/7
- ✓ **Energy Security**
  - A Secure Energy Source
- ✓ **Climate Friendly**
  - No Fossil Fuel Emissions
- ✓ **Facilitates Water Desalination***



* A Preliminary Assessment of OTEC Resources ASME 3/2007

OTEC: Onshore vs. Offshore

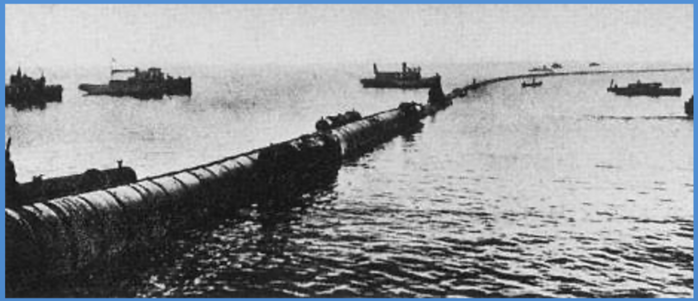


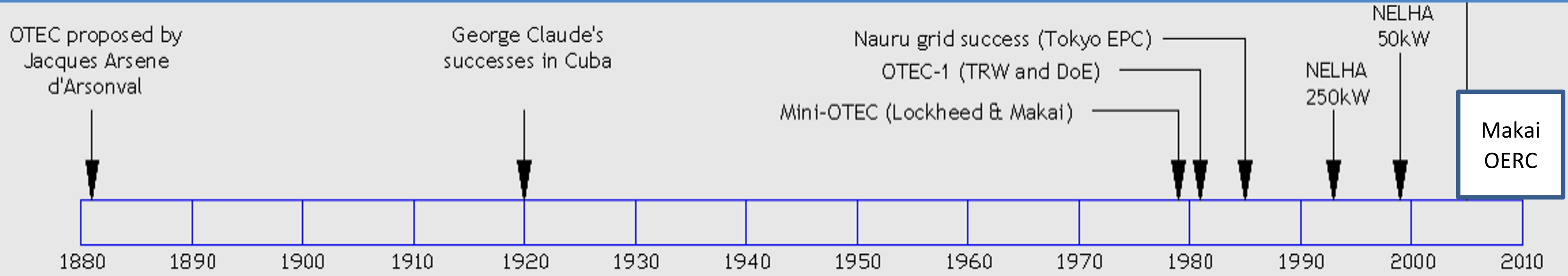
Dilemma: the necessary thermal gradient is found at sea, but the power it can generate is needed on land. This leads to two choices:

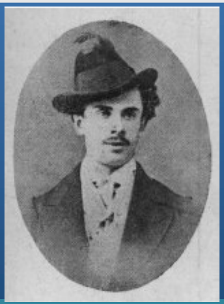
Onshore - OTEC plants built on land can easily transfer their electricity into commercial power grids, but don't have immediate access to the thermal gradient. The costs and complexity of building and running the plant on land are typically less, but the engineering required to convey the huge quantities of seawater to shore makes electricity generation projects economically unattractive.

Offshore - OTEC plants built on ships at sea sit right on top of the thermal gradient but face challenges operating at sea and in transmitting the power they produce to shore. They also require a large vertical pipe to upwell deep cold water. Despite these challenges added by working offshore, <u>it is generally accepted that OTEC is only economically viable when built offshore for utility scale power generation.</u>

OTEC: History

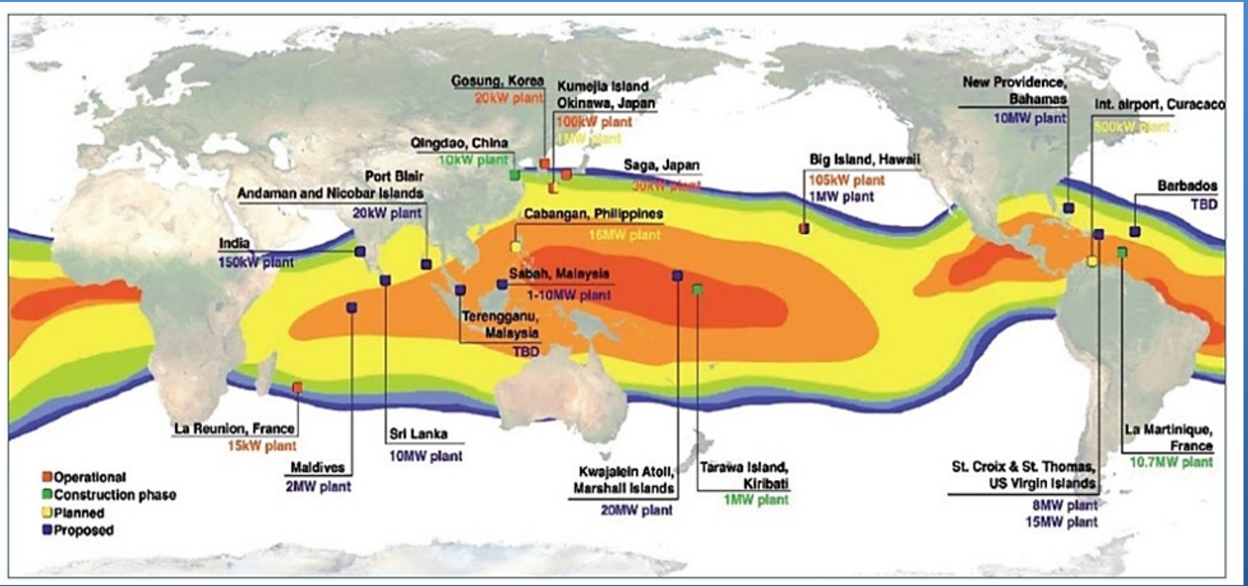






OTEC: Developments

- Currently, only two OTEC plants are operational, one in Okinawa the other in Hawaii, and both are onshore research facilities.



BARDOT OCEAN genius energy

Bluerise harnessing the ocean's power

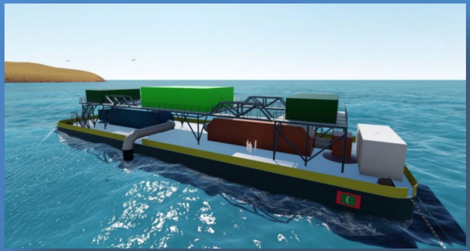
OCEAN THERMAL ENERGY CORPORATION

NAVAL ENERGIES

LOCKHEED MARTIN

GLOBAL OTEC

OTEC: Offshore Floating Utility Scale



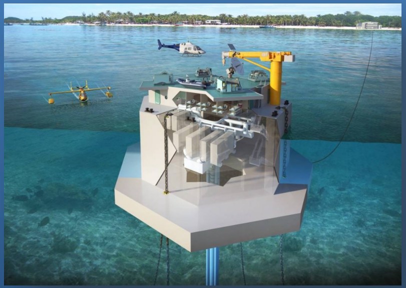
Global OTEC

Lockheed Martin

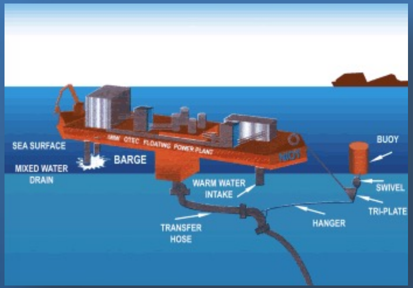
- Various designs proposed:
  - **Barge**
  - **Semi-submersible**
  - **FPSO-style**
  - **Spar**

Makai

Naval Energies



KRISO



NIOT

OTEC: Makai Research Center 100kW

- World's largest operational OTEC plant
- First to connect cc-OTEC to U.S. grid
- Plant dedicated Aug 21st 2015

Project Goals: <u>REDUCE COST OF OTEC</u>

- Develop autonomous OTEC plant controls
- Produce utility-grade electricity
- Gain operational experience
- Improve commercial designs
- Raise visibility of OTEC

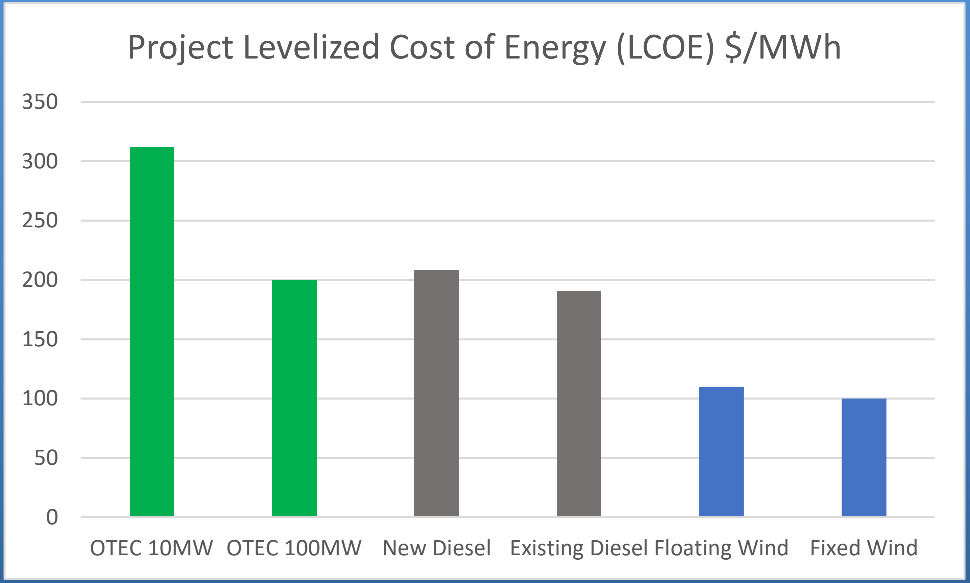
OTEC: KRISO 1MW Floating Plant

- Korea Research Institute of Ships & Ocean engineering (KRISO), has completed (2019) construction of a 1MW floating plant.

- This is presently under test in Korean waters. It is ultimately intended for Kiribati, Tarawa.

- At 1MW it is the largest single OTEC power plant and only the second to be tied into a commercial electrical grid.

OTEC: Cost Comparison



Above figures from Makai techno-economic modeling (2020) and Government data (diesel generators) for a Caribbean island nation.

- OTEC has vigorous economies of scale.
- At larger plant sizes, OTEC can be competitive with diesel generators.
- There is still a cost challenge to compete with more mature offshore wind.
- However, significant cost reduction opportunities with:
  - Heat exchangers
  - Cold water pipe
  - Platform design

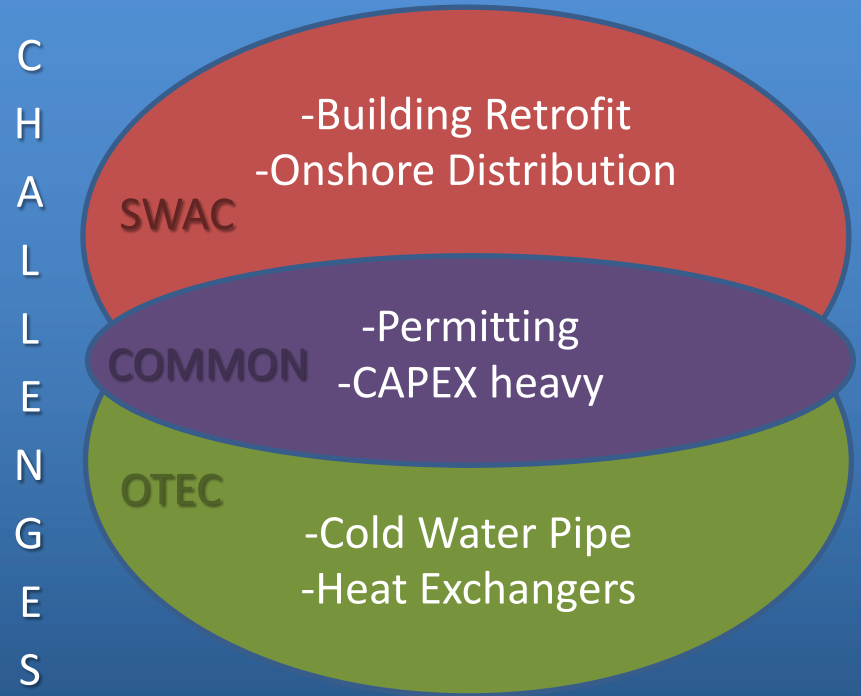
Summary and Challenges

SWAC

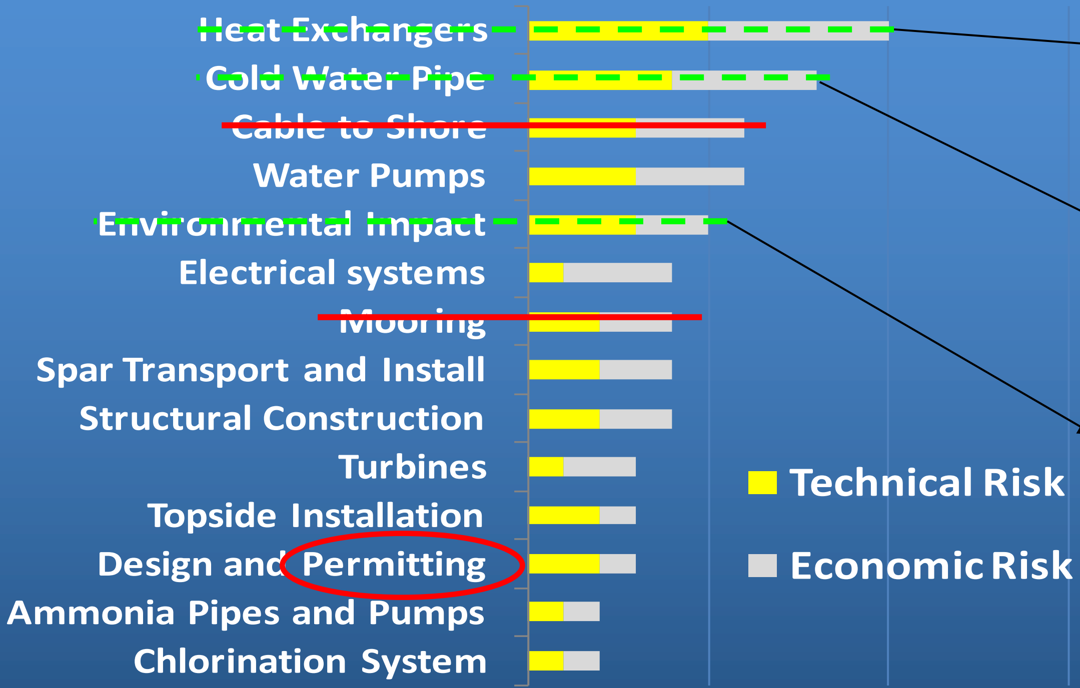
- Technically mature
- Proven economics
- Successful project history
- Continued pipeline of projects

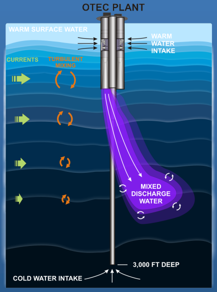
OTEC

- Still cost challenges
- Vigorous economies of scale
- Onshore OTEC limited to small scale
- Offshore floating pilot plant needed



OTEC: Grazing Opportunity





- Significant technical advancement over past two decades

- Reduced CAPEX
- Streamlines permitting
- Accelerated Deployment

OTEC Hydrogen?

"Integration and Optimization of Hydrogen Production with OTEC Technology in Offshore Floating Platforms".

In a world absent of oil, is OTEC a credible H_2 supplier?

- Benefits with H2, but many challenges
- Hydrogen an energy carrier, not an energy source
- DOE's hydrogen program ignores OTEC

OTEC: Fit to US DOE Hydrogen Economy

TABLE 1: HYDROGEN PRODUCTION FROM DOMESTIC RESOURCES TO PRODUCE 40 MILLION SHORT TONS OF HYDROGEN FUEL FOR 150 MILLION VEHICLES

Resource	Needed for Hydrogen Annually	Resource	Footprint Required
Reforming and / or Partial Oxidation			
Natural Gas	95 million tons	49 years	400 plants
Coal	310 million tons	89 years	280 plants
Biomass	400-800 million tons	n/a	400 - 600 plants
Water Electrolysis or Thermo-Chemical			
Wind	555 GW_e	n/a	North Dakota Class 3 Wind
Solar	740 GW_e	n/a	3750 sq. miles
Nuclear (electrolysis)	216 GW_e	n/a	200 plants
Nuclear (thermo-chemical)	300 GW_{th}	n/a	125 plants
Above information is condensed from [3].			
OTEC	216 GW_e	n/a	500 - 1000 plants

OTEC: Hydrogen or Ammonia?

In the future, fossil fuels rare and expensive:

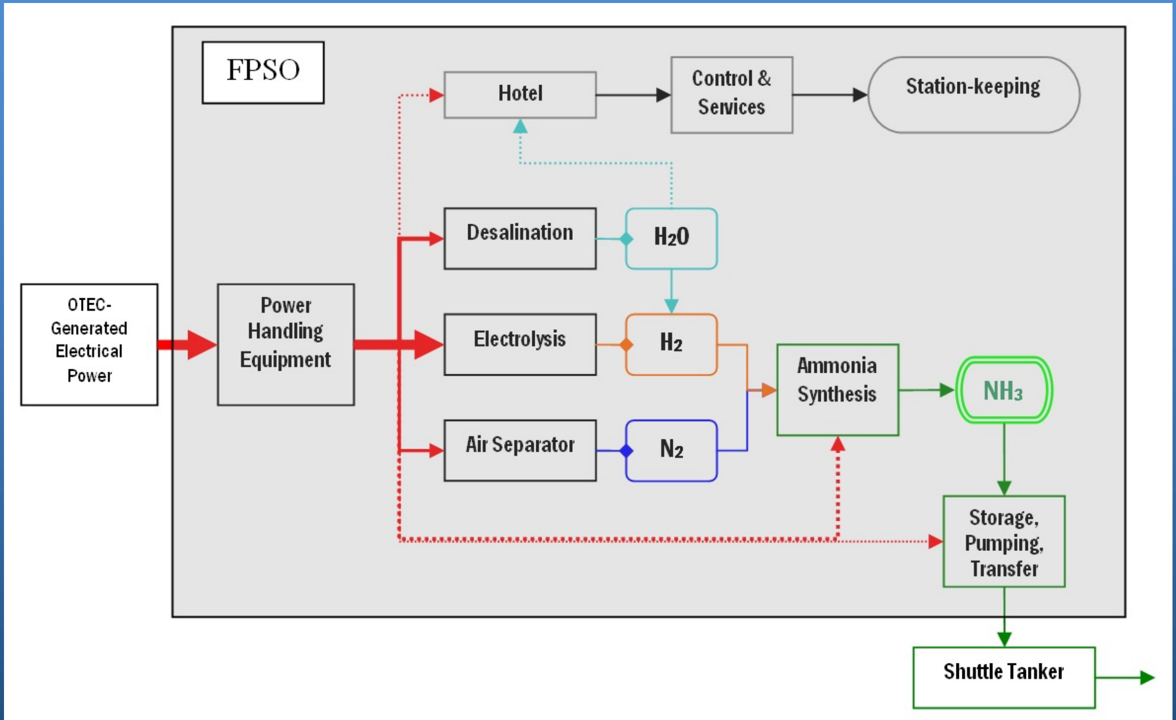
- Hydrogen economy envisioned by DOE
- Coal is limited resource, CO2 risks
- Nuclear could be unlimited, but NIMBY and waste disposal issues

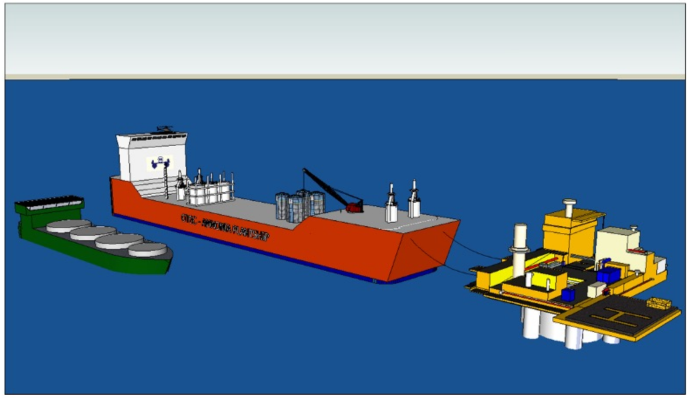
OTEC should at least be considered alongside other sources of hydrogen:

- The only renewable with massive potential for power production
- Could be economically competitive with other renewables
- Ammonia may be a good intermediate step

- OTEC has challenges, but so does the H2 economy

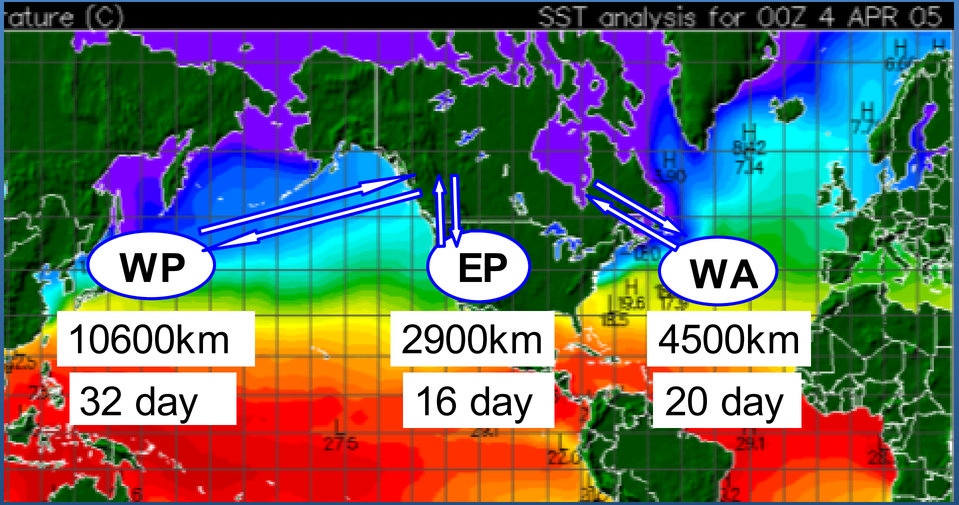
OTEC: Ammonia Grazing Plant Concept



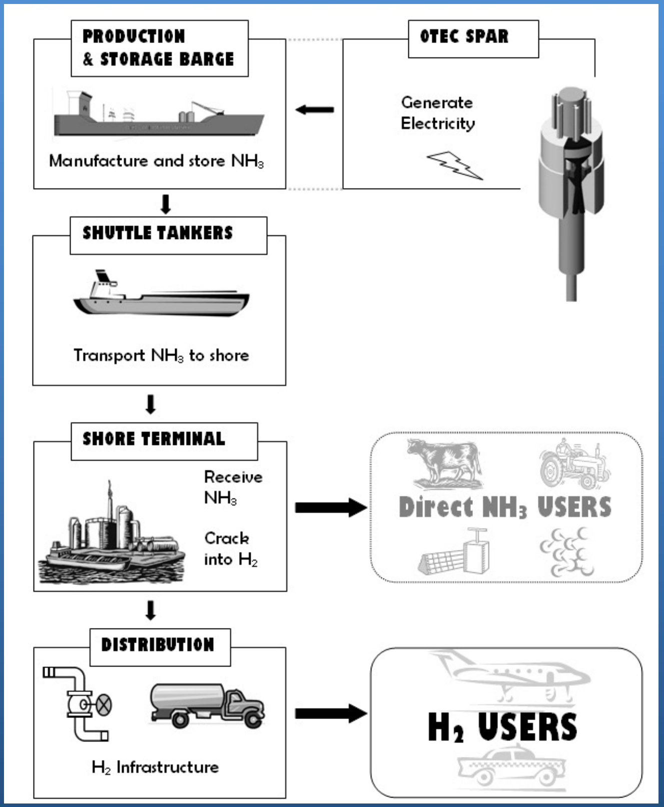


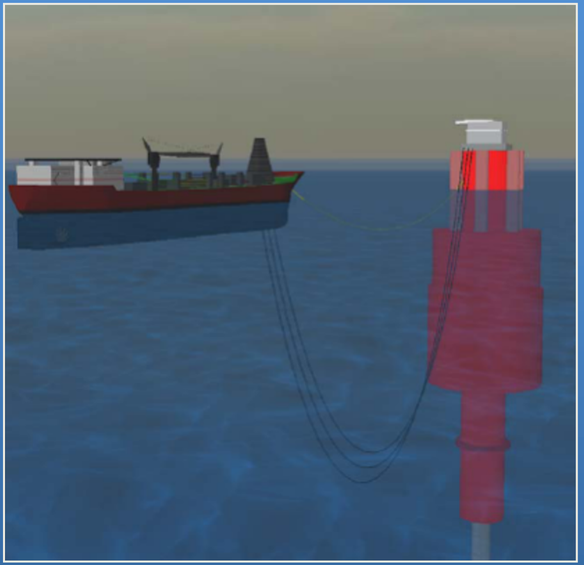
Global Vision 2050

- Hydrogen fuel for 150 million vehicles (DOE)
- Uses Ocean not US land
- Shorter routes than to import oil



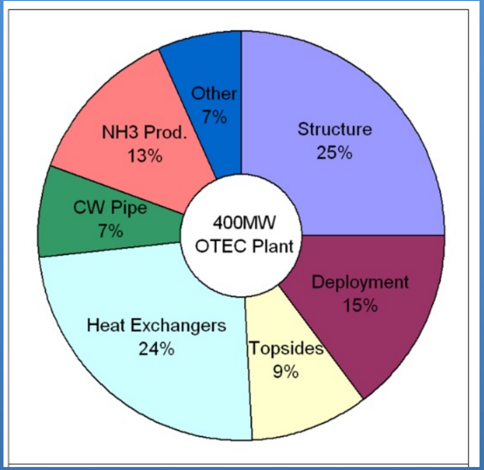
Logic of OTEC Ammonia Industry

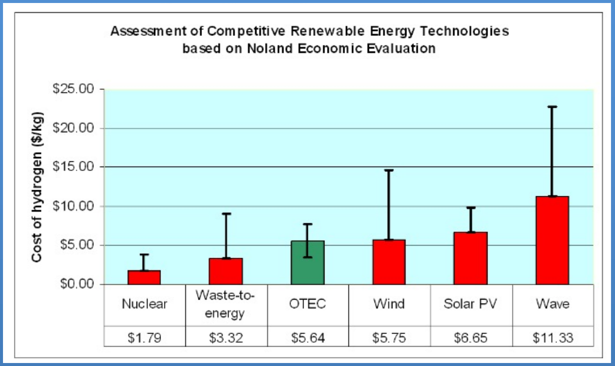


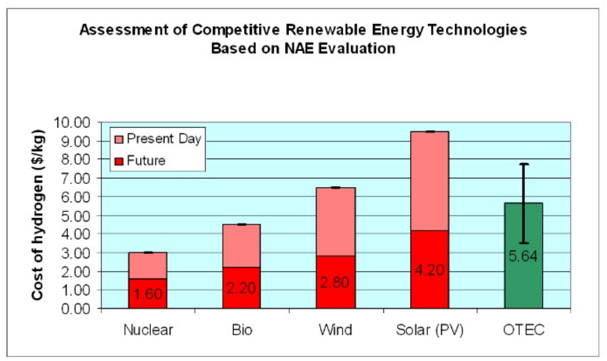


OTEC NH3 Fleet	1033 t/day (400MW)	700 Plants

Cost of OTEC Hydrogen Compared

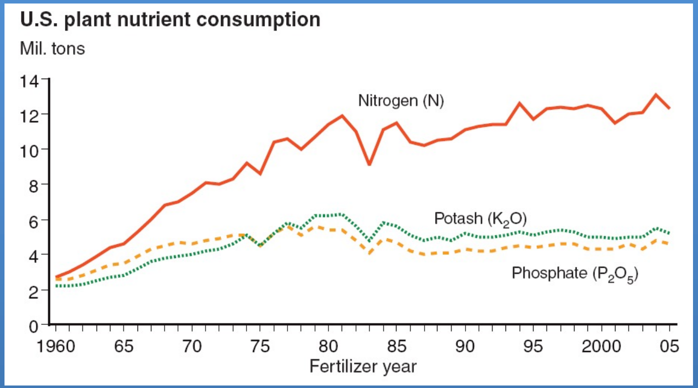


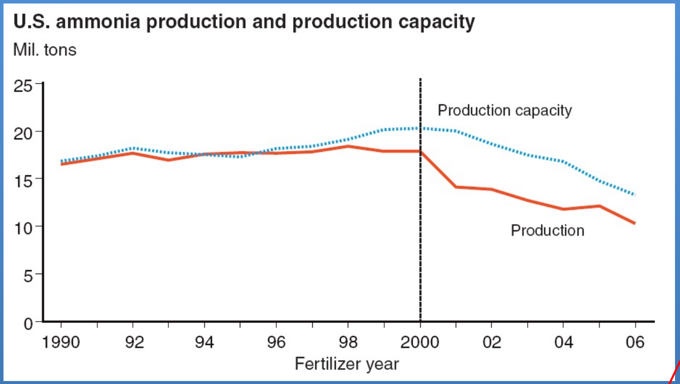




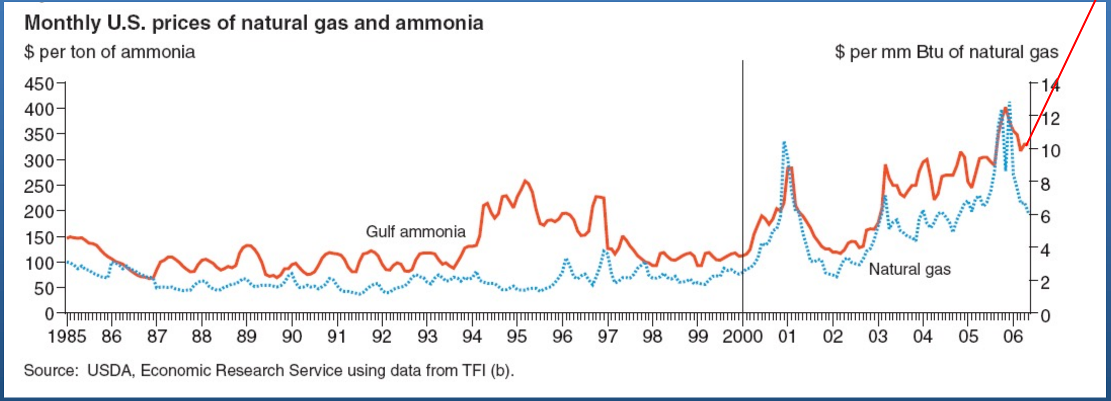
OTEC-NH_3 PLANT	**400 MW**	**$2.52bn** (capital cost)

Ammonia as a direct product





2022: $1000/ton!



Is there an opportunity to sell OTEC-Ammonia?

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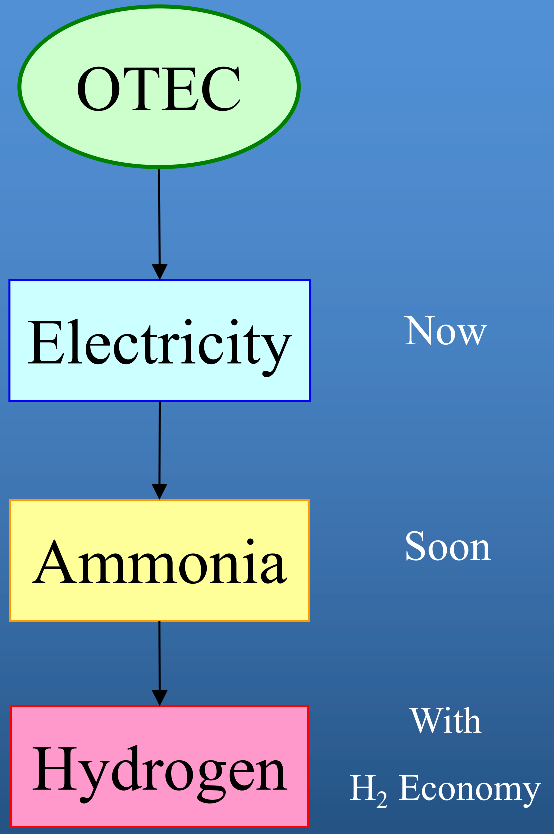
Conclusion

- OTEC is technically feasible
- OTEC is economically viable for electricity today
- Ammonia looks promising as an intermediate energy carrier
- In H2 economy, OTEC should be considered alongside other renewables
  - Large sustainable resource
  - Continuously available
  - Cost competitive



Next Step

Medium scale (~10MW) grid connected pilot plant
Location?

50kW (1970's) ✓

1MW (2019) ✓

10MW

Mahalo!