Duke University | Bass Connections

Marine Renewable Energy in the Republic of Mauritius

Team Members: Brandon Morrison, Cassidee Kido, Dhara Patel, Hallie Cramer

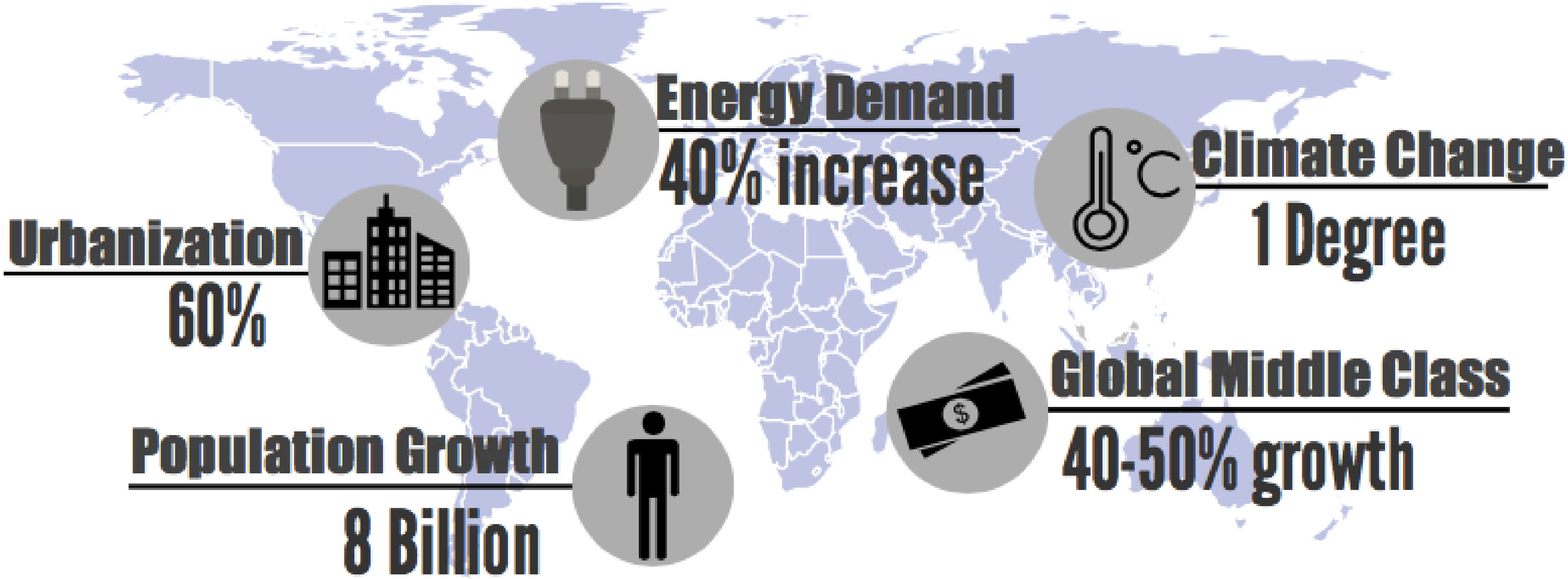
Faculty Leaders: Christina Reichert, John Virdin, Jonas Monast

Agenda

- **Drivers of Marine Renewable Energy and Context for Project**
- **Research Question and Methodology**
- **Results to Date**
- **Implications for Mauritius**
- **Questions for Discussion**

Challenges of the 21st Century

By 2030…



Energy Demand
40% increase

Climate Change
1 Degree

Urbanization
60%

Global Middle Class
40-50% growth

Population Growth
8 Billion

Marine Renewable Energy Potential

Reliance of fossil fuels

75%

Susceptible to climate change

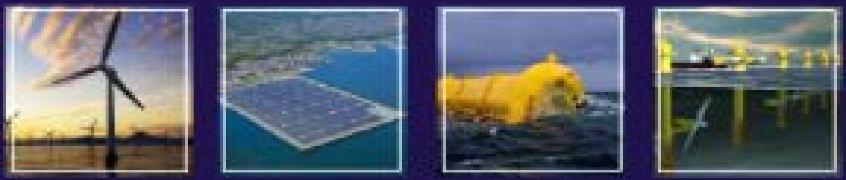
49cm

Upper-middle income country

$12B GDP

Enabling business environment

#32



Research Question:

What is the feasibility of developing and implementing marine renewable energy in Mauritius?

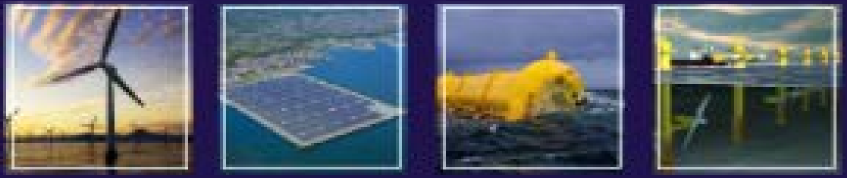
Methodology:

Comparative case study analysis of marine renewable technologies

Outputs:

1.) Summary of current research

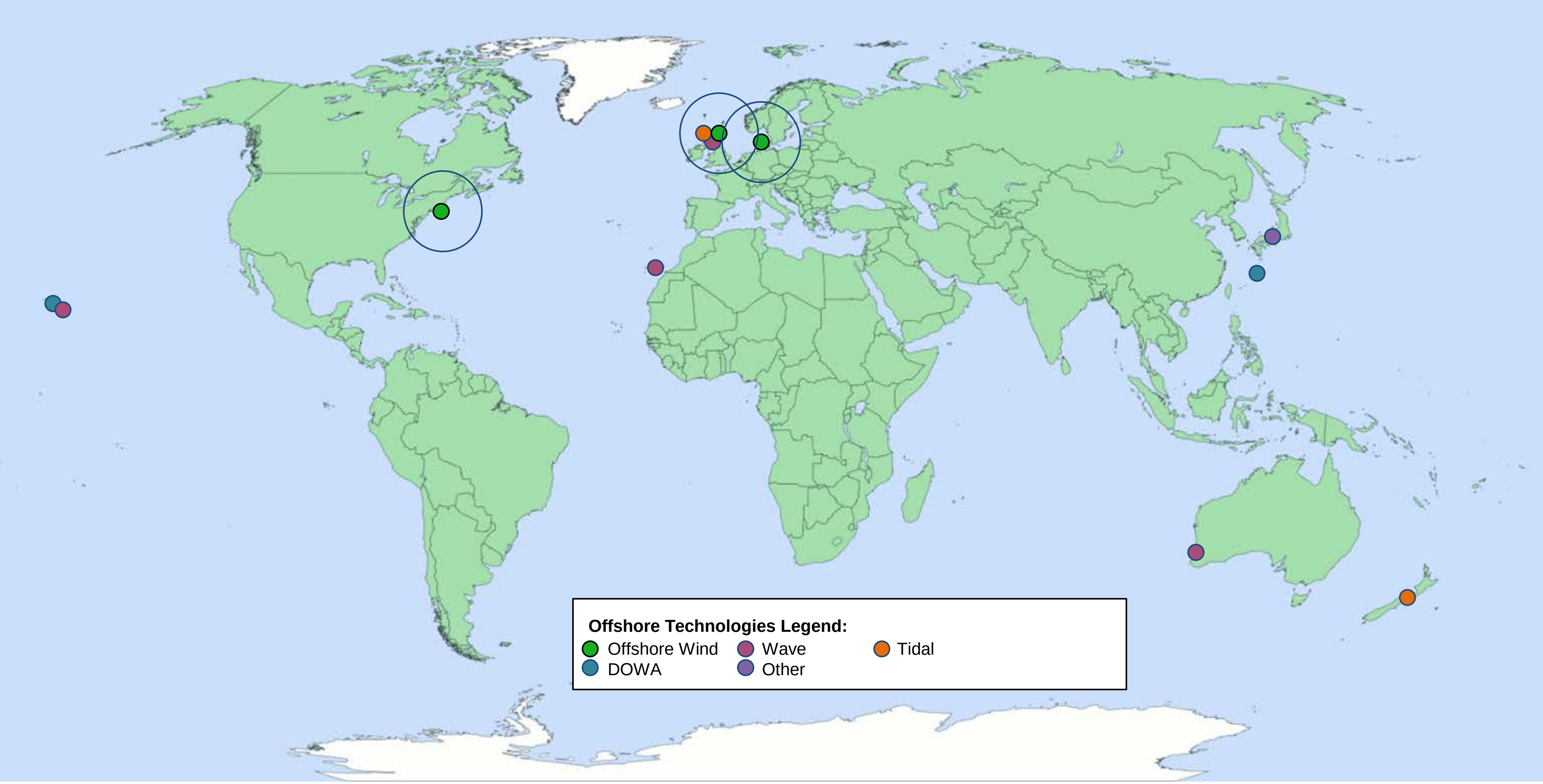
2.) Narrative summary write-up



Research to Date:

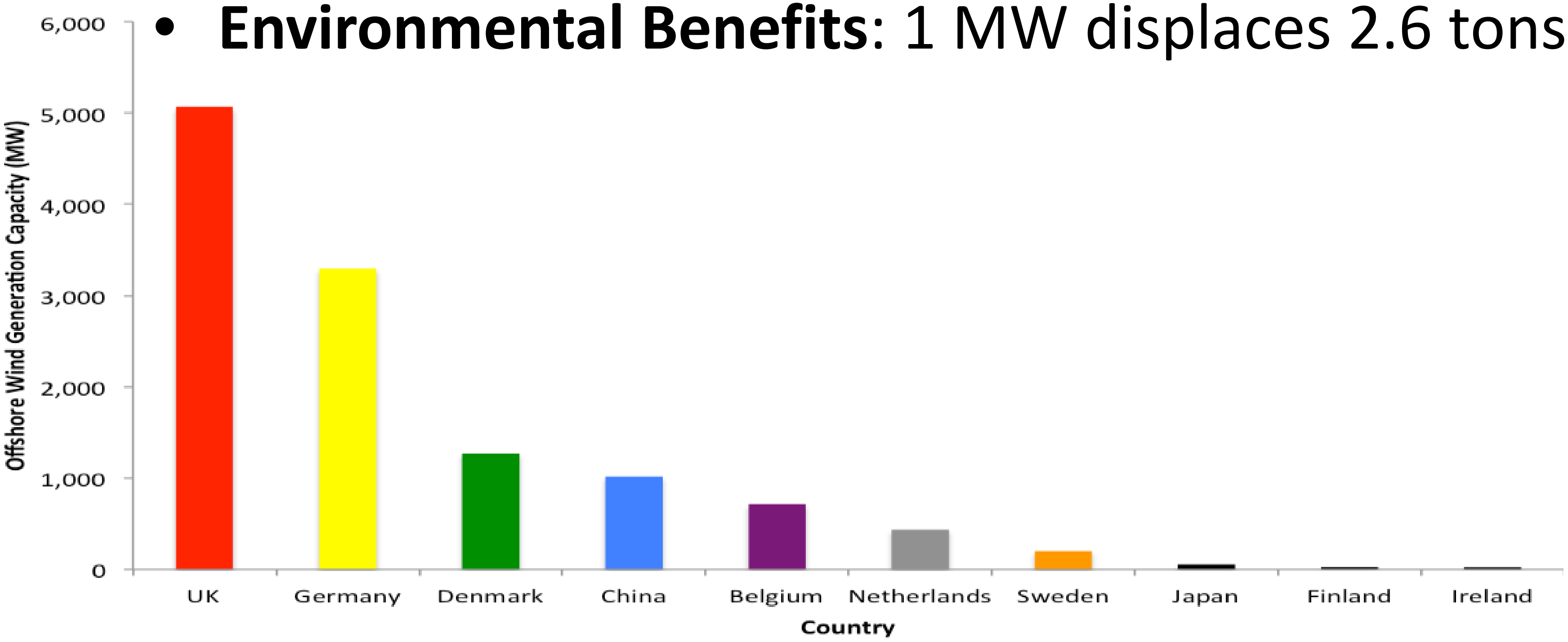
- In consultation with The World Bank and University of Mauritius, identified six technologies to investigate
  - Technologies: Offshore wind, wave, tidal, deep ocean water applications, floating photovoltaic, algal biogas
- Literature review, analyzing driving factors and commonalities
  - Case studies for each technology, focusing on a specific geographic locale
- Group synthesis of research in regards to implications for Mauritius in their pursuit of marine renewable energy

Technology #1: Offshore Wind



Technology #1: Offshore Wind

- **Technology**: Utility-scale; 12,000 megawatts (MW)
- **Capital Cost**: \$3.7 Million (USD) per MW
- **Electricity Cost** (LCOE): \$0.10-0.17 (USD) per kilowatt hour (kWh)
- **Environmental Benefits**: 1 MW displaces 2.6 tons CO_2



Technology #1: Offshore Wind

Case: Block Island Wind Farm

- **Location**: 3 miles off of Block Island, RI
- **Capacity**: 30 MW; 6 turbines total
- **Cost**: \$290 Million (USD); \$0.24/kWh

- **Economic benefits: rates reduced by 40%**
- **Good Jobs**: 300 skilled workers
- **Clean Energy**: 40,000 tons reduction in CO_2

Technology #1: Offshore Wind

Case:
Denmark
Offshore
Wind

First offshore wind farm
1991

Third largest market
1,271 MW

Increased growth
200% last decade

Electricity cost
$0.08 (USD)/kWh

First-mover advantage
90% of global market

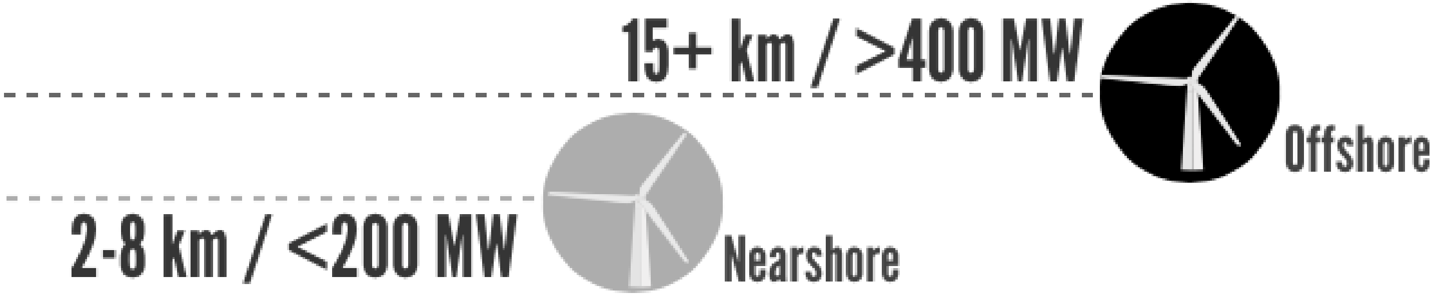
Technology #1: Offshore Wind

Case:
Denmark
Nearshore
Wind

Government Initiative

Community Buy-in

Decreased Cost


15+ km / >400 MW

Offshore

2-8 km / <200 MW

Nearshore

Technology #1: Offshore Wind

Case: Scotland

Capacity:

- Contains 25% of entire European offshore wind potential
- 197 MW of operational offshore wind
  - 4 GW have been granted planning consent

Barriers:

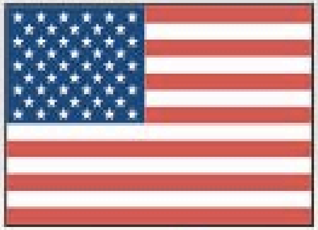
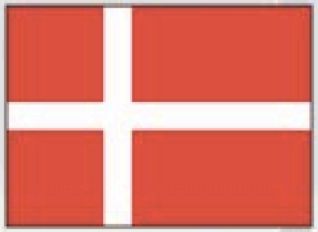
- Major transmission bottlenecks
- Power system stability
- High capital costs

Support:

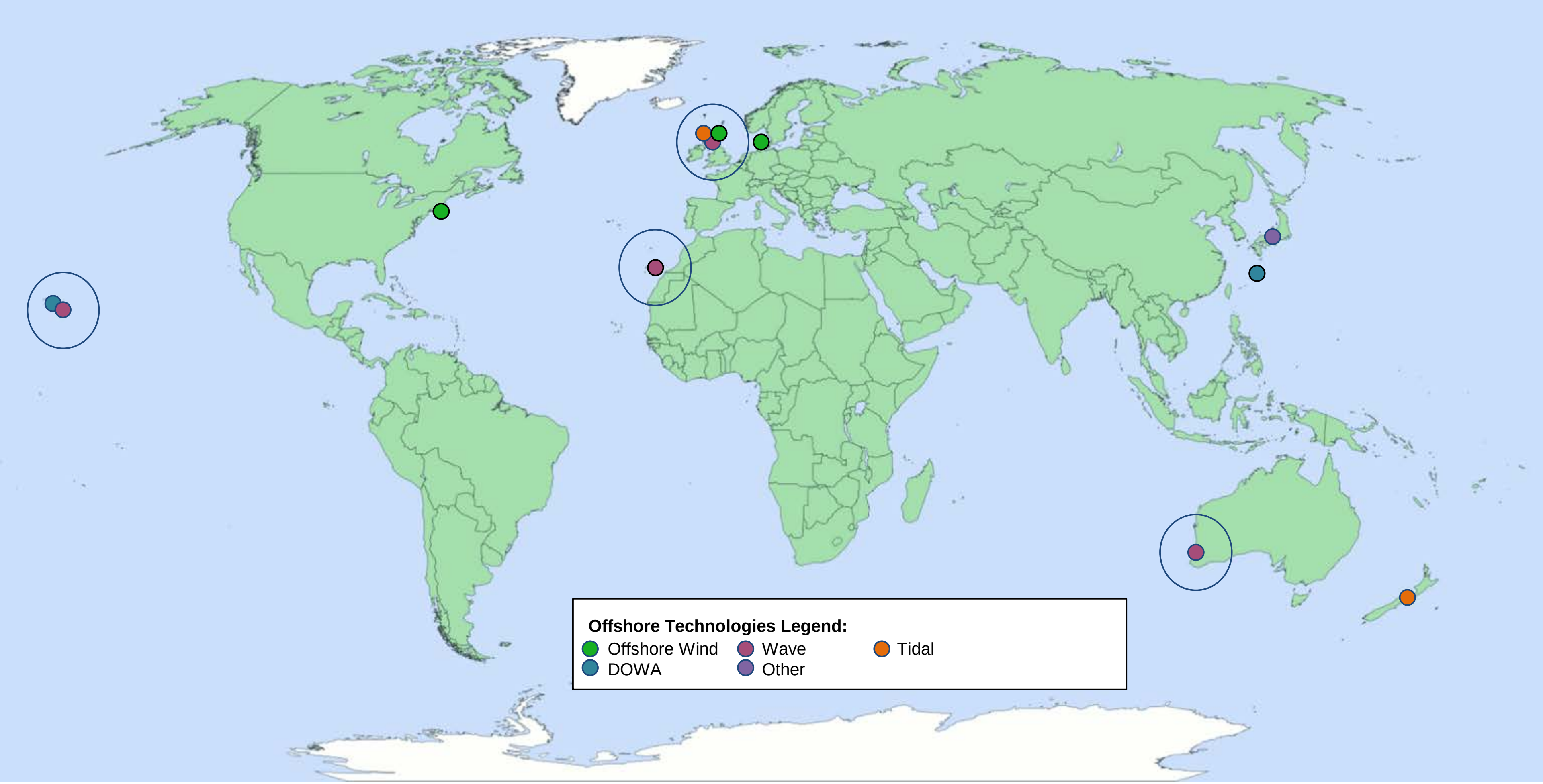
- Infrastructure
- Investment hubs
- Skilled workforce
- Supply chain
- Renewables obligation

Technology #1: Offshore Wind

Lessons Learned

			
1.	Government Support	Government Support	Government Support
	Private Development	Grid Connectivity	Economic Development
	Reduced Costs	Community Involvement	Grid Connectivity
	Community Involvement	Environmental Considerations	Private Development
	Environmental Considerations	Reduced Costs	Reduced Costs
	Economic Development	Economic Development	Environmental Considerations
7.	Grid Connectivity	Private Development	Community Involvement

Technology #2: Wave Energy



Technology #2: Wave Energy

Overview

Technology: Small number close to commercialization, over 100 projects worldwide

Generation Capacity: Demonstration farms approaching range of 10 Megawatts (MW)

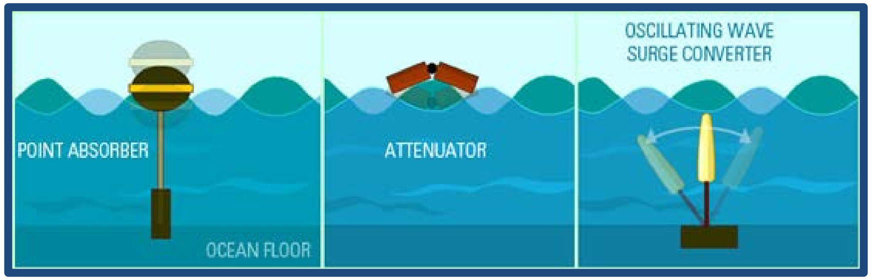
Where does it work best:

- Strong winds > 20 kW/m
- Usually between 40 and 60 d. lat.
- Deeper waters near shore

Capacity Factor: Between 30% and 50%

Costs

- **Electricity Cost** (LCOE): $0.37-0.70 (USD) per kWh for 10 MW deployment (2014 est.)
- **Capital Costs:** $7000/kW (2006 est.)
- **Variable O&M Costs:** $17/MWh (2006 est.)



Technology #2: Wave Energy

Case: Hawaii, U.S.

Project: Northwestern Energy Innovations (NWEI) grid-connected 20 kW Azura demonstration device at WETS 30m test berth

Research and Funding:

- Hawaii National Marine Renewable Energy Center (HINMREC) provides infrastructure
- U.S. DOE $9.7m in awards to Hawaii, $5m to NWEI

Government Involvement:

- Tax credits & clean energy bonds
- Renewable Energy Targets of 30% by 2020, 40% by 2030, and 100% by 2045
- U.S. regulatory process as primary hindrance

Technology #2: Wave Energy

Case: Canary Islands, Spain

Project: Langlee Wave Power open water system testing

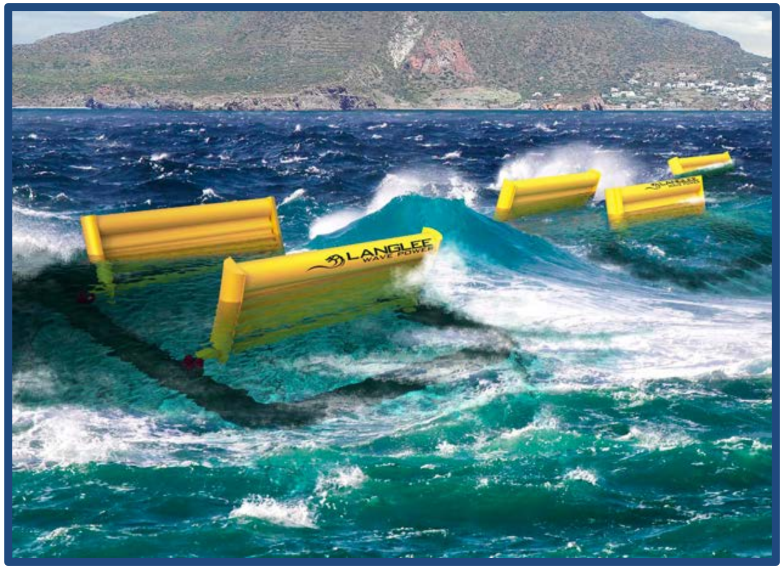
- Manufacturing site on north Tenerife Island
- 4400 operating hrs/yr at costs competitive to wind

Supporting Factors:

- Oceanic Platform of the Canary Islands (PLOCAN) main research hub
- Local government agreement

Barriers:

- Isolation of island grids
    - Red Electrica ~$890m investment in smart grid
    - Up to 2000m sea depth between islands
- Lack of financial support and strategic plans for ocean energy



Technology #2: Wave Energy

Case: Perth, Australia

Project: Carnegie Wave Energy Limited CETO 6 technology is world's first commercial-scale wave energy array connected to grid (3MW generation)

Financing:

- Invested over $100m
- $25m federal ($13m from ARENA) and $10m grant WA government
- Equity from 7,500 Australian shareholders & Clean Energy Finance Corporation (CEFC) five-year $20m loan facility

Goals:

- Large wave farms of 100MW would reduce LCOE to $0.12-0.15/kWh (currently $0.40/kWh)
- Aimed at island nations looking to be sustainable; “micro-grid”

Barriers:

- Lack of policy stability
- Gaining access to coastal waters
- Uncoordinated research effort

Technology #2: Wave Energy

Case: Scotland, UK

Capacity: Reports estimate up to 14 GW of recoverable wave energy

Barriers: grid capacity to the north of Scotland and within Orkney Isles

Support: Wave Energy Scotland --fully funded by the Scottish Government

Marine Spatial Planning: integrated planning policy framework to guide marine development

wave energy
SCOTLAND

Technology #2: Wave Energy

Lessons Learned

Advantages:

- Considerable scope for economies of scale and learning
  - 2030 estimate LCOE between $0.13-0.25 (USD)/ kWh if we can achieve more than 2 GW deployment level
- Less variable and more predictable than wind

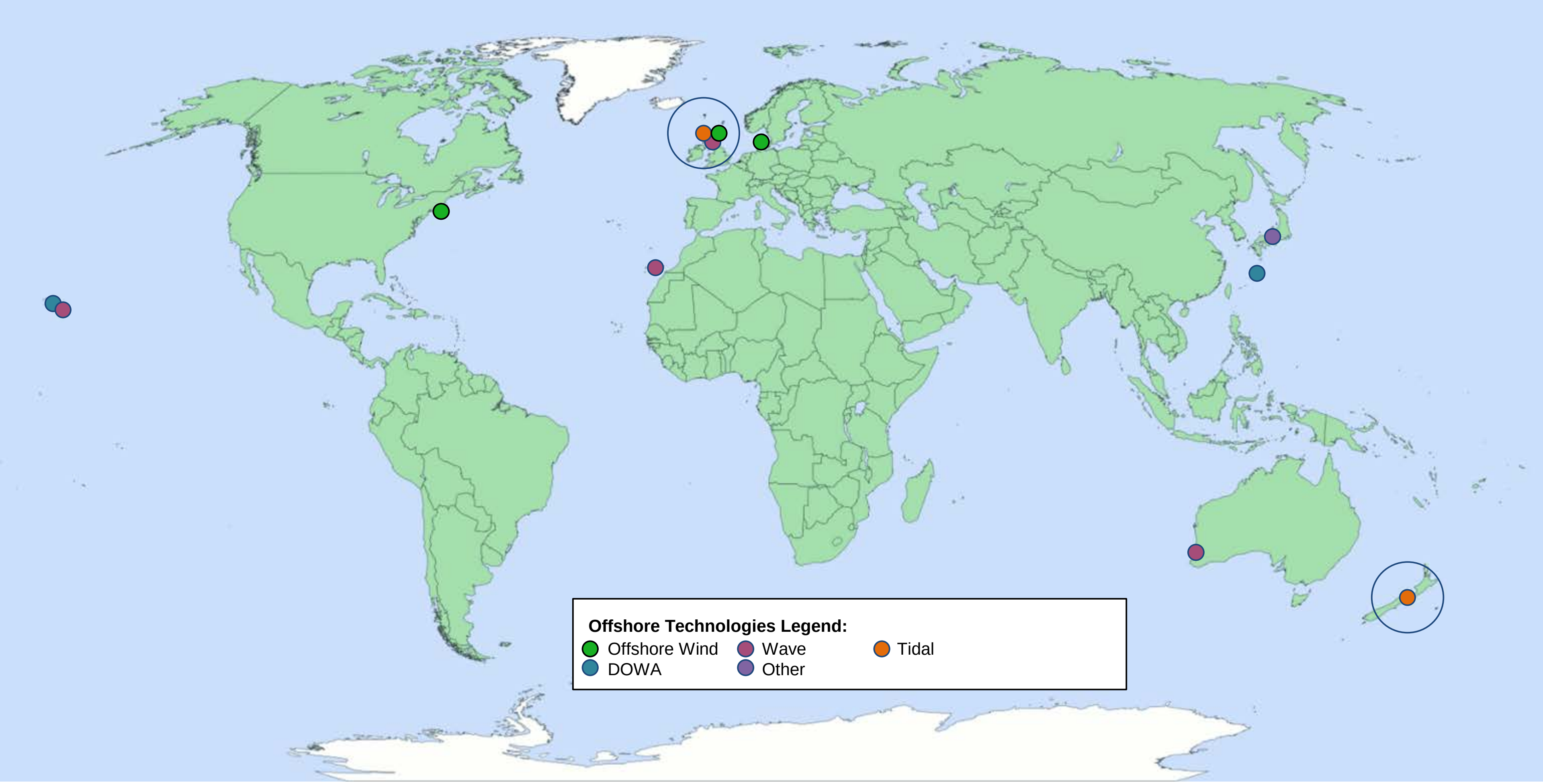
Barriers:

- Technological variance among converters and limited supply chain for components
- Lack of synergy with other offshore industries

Failures:

- Pelamis filed for bankruptcy in 2014
- OPT pulled out from Wave Power Project

Technology #3: Offshore Tidal



Technology #3: Offshore Tidal

Overview

Technology:

- Tidal range: commercial scale
- Tidal current/stream:full scale deployment (single turbines) and demonstration phase (arrays)
- Hybrid: project proposals in place

Generation Capacity:

- Technically harvestable tidal ~1 TW globally
- Tidal current ~120 GW globally

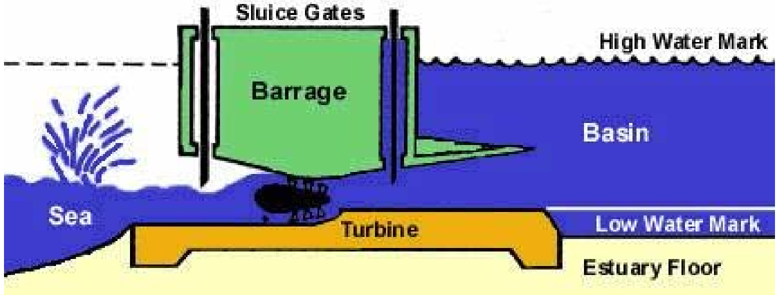
Electricity Cost: $0.28-0.52/kWh (USD)

Benefits:

- Predictable
- Available day and night
- Job creation
- Tidal range: not influenced by weather

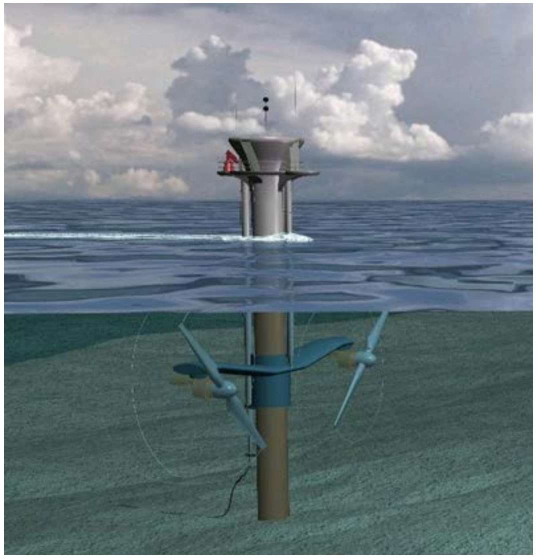
Downsides:

- high investment cost
- possible negative environmental impacts



Technology #3: Offshore Tidal

Case: New Zealand



Two main projects:

- Cook Strait: 7000 MW (2008 est.)
- Kaipara Harbour: 110-240 MW (2011 est.)

Supporting Factor: $4M Marine Energy Deployment Fund established

Barriers: Half a dozen proposed schemes in NZ were cancelled due to:

- Electricity market uncertainty
- Partial privatization of generators
- Uncooperative power companies
- Opposition from Maori people
- Diversion of investment
- Misdirection of state financial support

Technology #3: Offshore Tidal

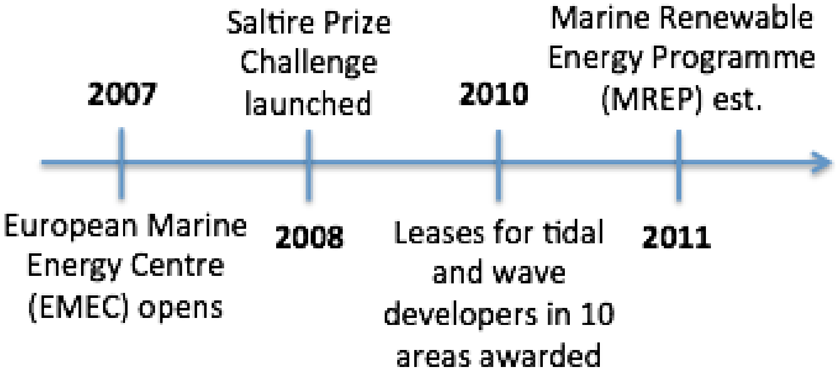
Case: Scotland

Potential:

- Scotland contains ~25% of Europe’s total tidal power
- Pentland Firth and Orkney Waters has 800 MW of capacity for tidal (over 50 MW elsewhere)

Main Project: MeyGen Project is largest planned tidal energy project in the world (~400 MW)

Supporting Factors: Marine Spatial Planning as well as:

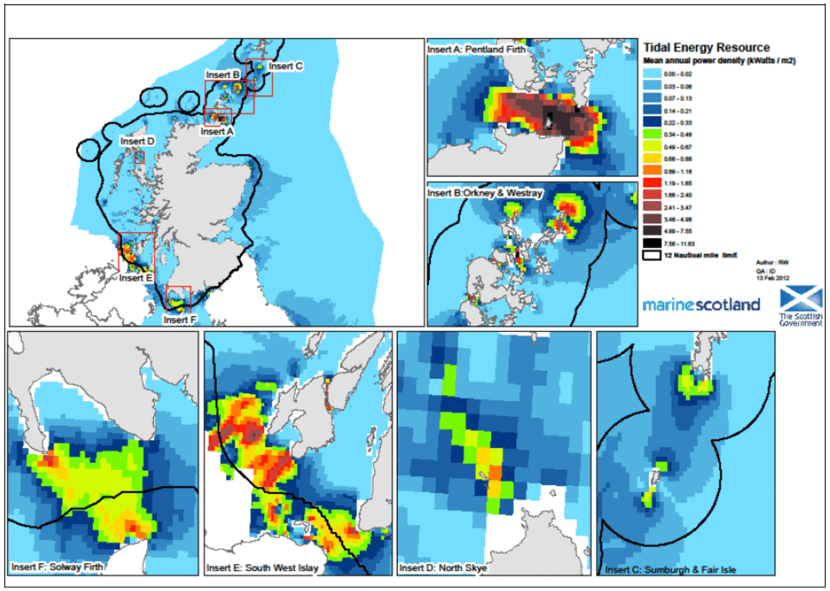


2007 – European Marine Energy Centre (EMEC) opens

2008 – Saltire Prize Challenge launched

2010 – Leases for tidal and wave developers in 10 areas awarded

2011 – Marine Renewable Energy Programme (MREP) est.



Technology #3: Offshore Tidal

Lessons Learned

Advantages:

- Availability of the tidal energy is predictable, produced throughout the day, and not influenced by weather (tidal range)

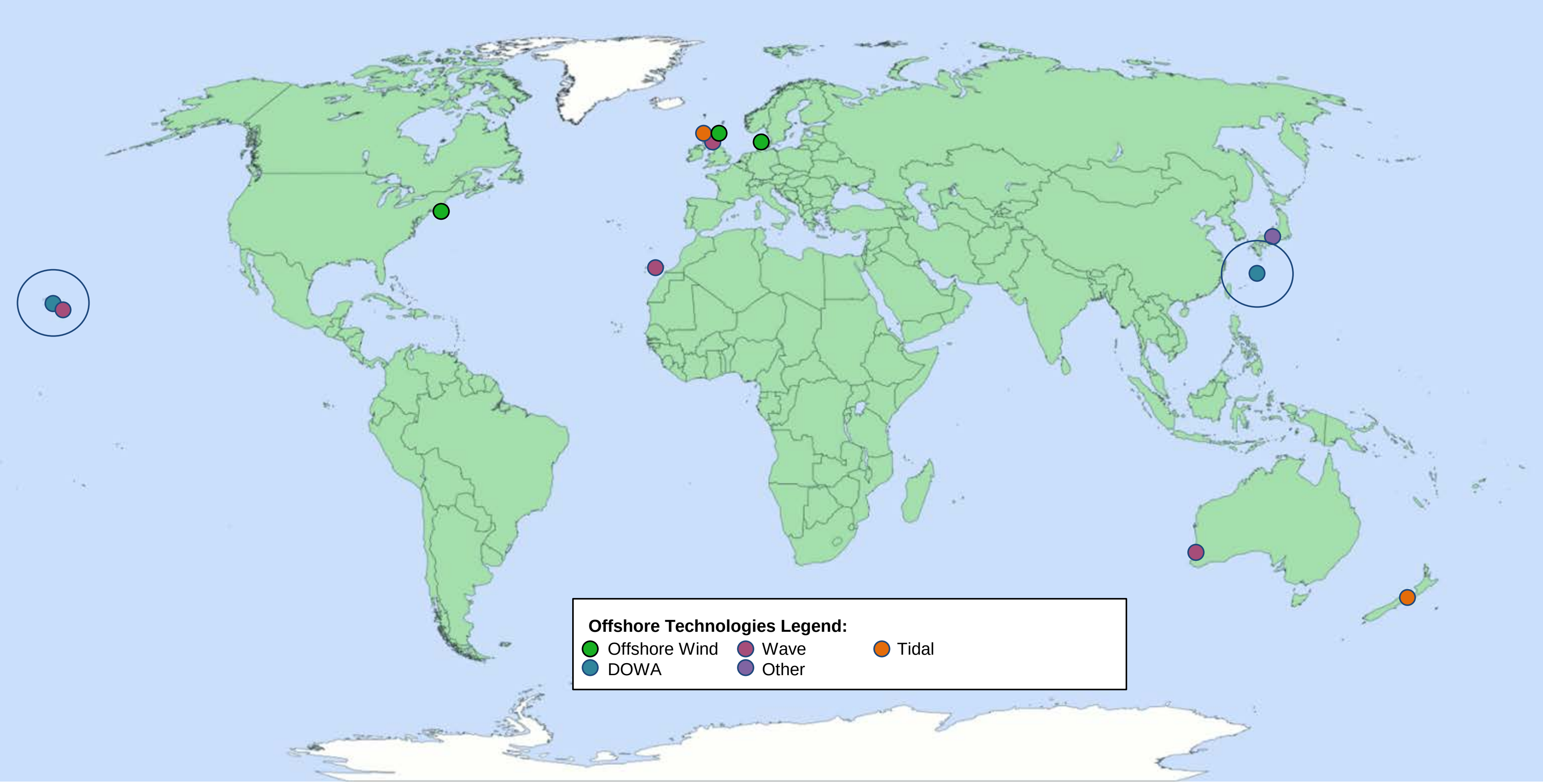
Downsides:

- Capacity factor of only 25%
- High capital costs
- Turbines impact current flow
  - Possibility of other environmental impacts still unknown

Barriers

- Electricity market uncertainty
- Partial privatization of generators
- Uncooperative power companies
- Opposition from Maori people
- Diversion of investment
- Misdirection of state financial support

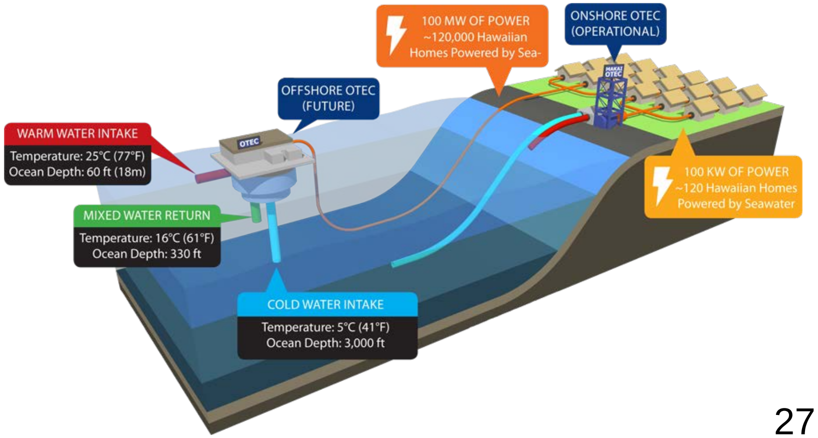
Technology #4: Deep Ocean Water Applications



Technology #4: Deep Ocean Water Applications

Ocean Thermal Energy Conversion (OTEC)

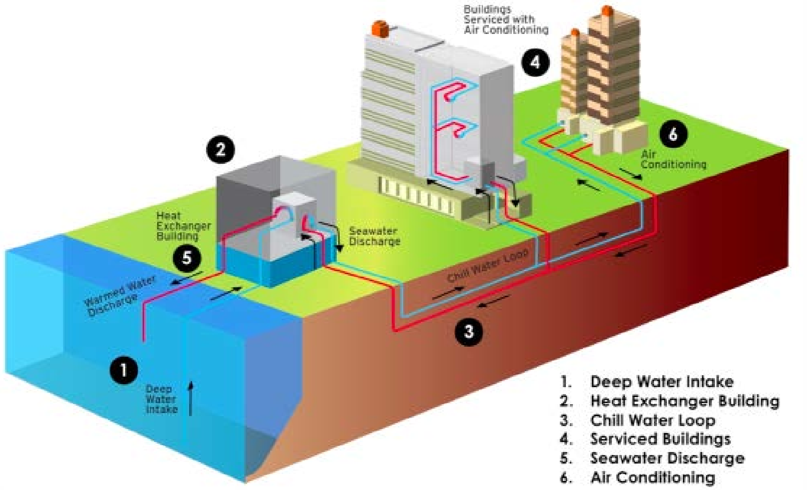
- **Technical Challenge:** have only built plants up to 1MW
- **Estimated Costs:**
  Overhead costs: between \$16,400 and \$35,400/kW (2010 USD); capital intensive, heat exchanger main component
  Electricity Costs (LCOE): Around \$0.51-0.94/kWh for 1-1.35 MW plant
- **Capacity Factor:** between 90% and 95%
- **Ideal conditions:**
  Large temperature differential between surface water (~77 d.) and deep ocean water (~40 d.)
  Close access to cold deep ocean water, flat shelf



Technology #4: Deep Ocean Water Applications

Seawater Air Conditioning (SWAC)

- More than seven institutions or cities worldwide utilize this technology
- **Size:** Systems range from 50 to 58,000 tons (city scale)
- **Estimated Costs:**
  - Slightly less than $1,500/ton/yr, majority capital costs
  - Conventional system much more energy intensive with costs around $3000/ton/yr
  - Short economic payback period ranging from 3 to 7 yrs
- **Energy savings:** 80% to 90%



Technology #4: Deep Ocean Water Applications

Case: Hawaii, U.S.

Project: 105kW OTEC pilot plant and SWAC implementation at Natural Energy Laboratory of Hawaii Authority (NELHA)

Advantages:

- 12 commercial-scale plants could meet 100% of Hawaii's power needs
- NELHA is world's premier OTEC research center

Barriers:

- 10MW plant planned for 2013 but was shelved due to costs
  - 105 kW OTEC plant cost $5m to build
- For LCOE to approach $0.07-$0.19/kWh, need 100MW plant

Technology #4: Deep Ocean Water Applications

Case: Okinawa, Japan

Project: 0.1MW OTEC plant and SWAC implementation at Kumejima Okinawa began generation in 2013

Drivers:

- 21st Century Vision of Okinawa
- Goal of 100% sustainable by 2020
- Deep seawater pipeline installed in 2003

Benefits:

- Helps realize a low-carbon island society
- Multiple uses for industrial park around Deep Water Facility

Technology #4: Deep Ocean Water Applications

Lessons Learned

Ocean Thermal Energy Conversion (OTEC)

Future development and economies of scale highly dependent on:

- Financing options
- Steep learning curve

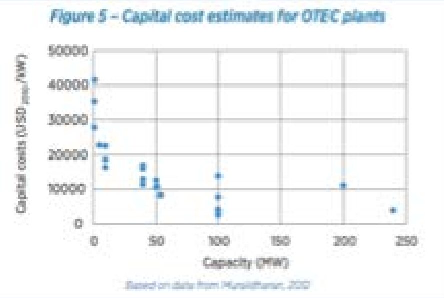


Figure 5 – Capital cost estimates for OTEC plants

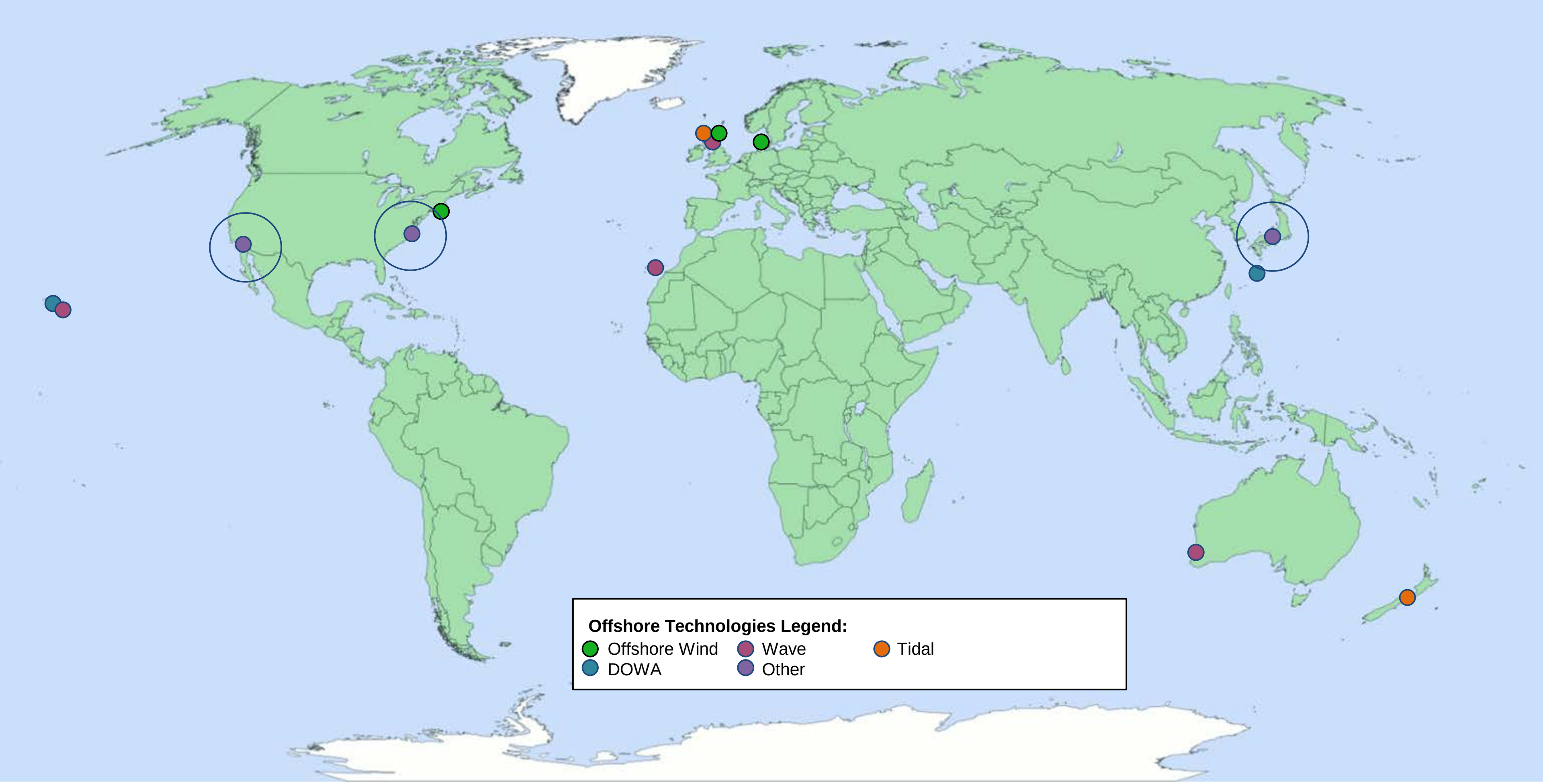
Based on data from Muralidharan, 2012

Seawater Air Conditioning (SWAC)

Economic viability increases when:

- Systems greater than 1,000 tons
- Distance to offshore cold water (approx. 200m deep) is shorter
- High percent utilization of AC system
- High local LCOE
- District cooling arrangement with compact distribution

Case Study Locations: Other



Technology #5: Floating Photovoltaic

Case: Japan

Technology:

Utility-scale (and proposed) in Australia, India, U.S., Brazil and Korea

Generation Capacity:

13.4 MW, will deliver 15,635 MWh/year

Capital Cost:

$3.7 Million (USD) per MW

Electricity Cost:

Sold back to Tokyo Electric Power Co. for $78.7 million/year

Environmental Benefits:

- Generate 20% more energy
- Reduce evaporation
- No heavy-duty equipment
- Less energy waste
- Reservoirs for agricultural and flood-control purposes

Barriers:

- Few approved feed-in-tariffs implemented

Case Studies: Lessons Learned

Technical

- Coordinated research effort and testing facility important for development
  - Need to test technology through life cycle in all conditions to ensure confidence in devices
- MSP key in optimizing tradeoffs of ocean space

Political

- Certain permitting and licensing processes hinder development
- Financial incentives necessary
- Encouraging demand side push gives investors confidence

Economic

- High upfront costs and capital investments impede project development
- Can create local employment opportunities and growth in manufacturing sector
- Domestic supply chain reduces costs
- Stakeholder engagement and communication critical

Implications for Mauritius

Implications for Mauritius: Offshore Wind

Mauritius

- 250 MW
- Batelle Report and Mauritius Research Council
- Proposed projects
- Hexicon

Block Island, Denmark Offshore and Nearshore, Scotland

- Advantages
  - Revitalization of industrial ports
  - Nearshore farms are more competitive
- Disadvantages
  - Costly grid updates
  - Plans for support mechanisms

Implications for Mauritius: Wave Energy

Mauritius

- Carnegie Wave Energy
- Perth Project and Garden Island Project
- Grant partnership of $560,000, technical support of $130,000

Hawaii, Canary Islands, Australia, Scotland

- Advantages
  - Predictability
- Disadvantages
  - Lack of synergy with other offshore industries
  - Technological variance among converters

Implications for Mauritius: Tidal

Mauritius

- "Investigating the Appropriate Renewable Energy Technologies in the Mauritian Context" by Jeetha Devi

New Zealand and Scotland

- Advantages
  - Predictable
- Disadvantages
  - High capital costs
  - Impact current flow

Implications for Mauritius: OTEC & SWAC

Mauritius

- Deep water nearness

SWAC

- Economic viability increases when:
  - District cooling arrangements
  - Compact distribution

OTEC

- Future development dependent upon:
  - Steep learning curve
  - Financing options

Implications for Mauritius: Other

Mauritius

- "Investigating the Appropriate Renewable Energy Technologies in the Mauritian Context" by Jeetha Devi
- Familiarity with bagasse

Floating Photovoltaic

- Japan 13.4MW plant Okinawa

Algae Biogas

- DOE and California Energy Commission/ NASA
- Labor for carbon dioxide and restricted access
- Byproducts used in high-value items

Next Steps:

Transparent policy strategy and energy plan to promote offshore development

Focus on assessing energy potential and providing infrastructure: OTI, research center, supply chain

Friendly business environment to facilitate expansion of international businesses in Mauritius

Clear permitting and licensing framework; extra cautious of environmental effects

Marine Spatial Planning to offer greater clarity to decision making in the marine environment and encourage economic investment

Knowledge Gaps and Future Research

- Large variance in cost estimates and scope for economies of scale
- Establishing well-thought out offshore energy strategies by governments
- Expertise necessary to maintain technology structures
- Unknown environmental risks

Questions?

Team Members:

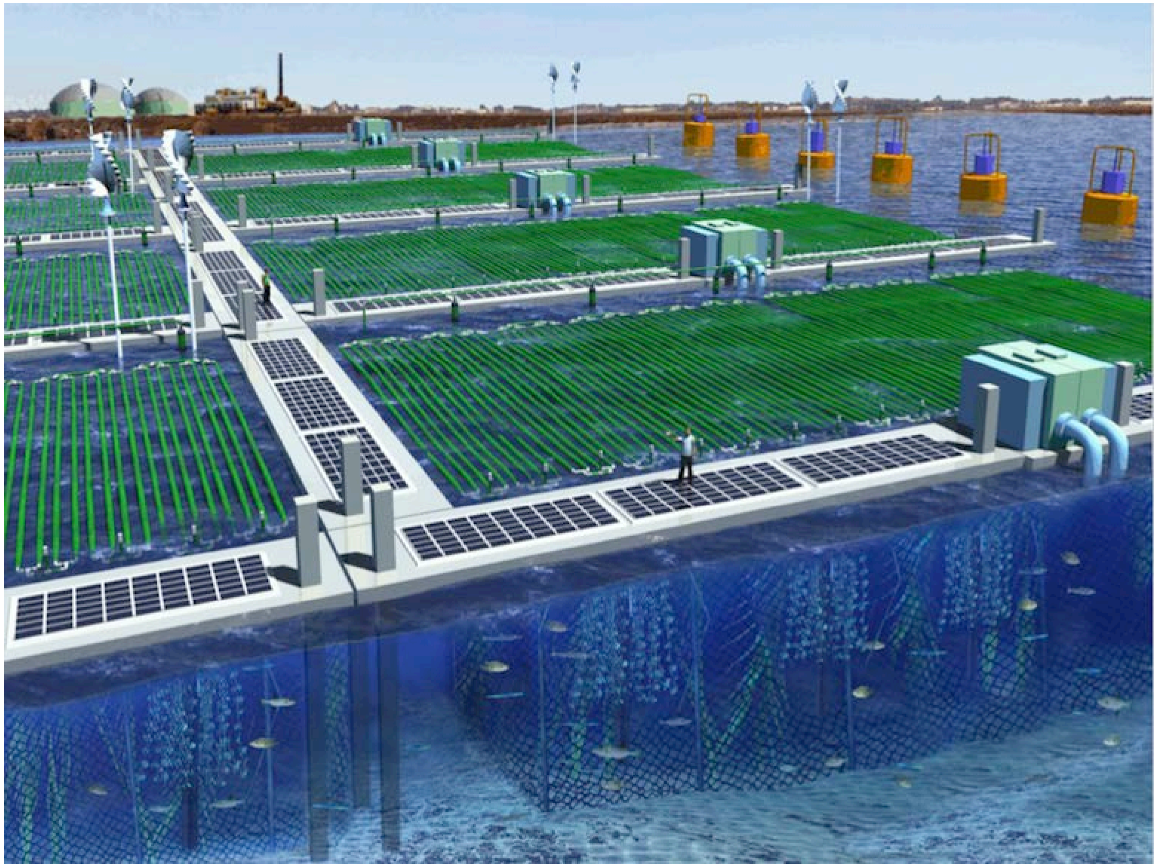
Brandon Morrison – Brandon.Morrison@Duke.edu
Cassidee Kido – Cassidee.Kido@Duke.edu
Dhara Patel – Dhara.Patel@Duke.edu
Hallie Cramer – Hallie.Cramer@Duke.edu

Questions for Discussion

- What policy options and incentives are available in Mauritius to promote and develop renewable energy?
- What further information would be useful to include in the white paper?
- What role does the Central Electricity Board (CEB) - as the sole organization responsible for electricity generation - see in offshore renewable energy?

Algae Biogas Summary

Cases: MAGIC (Duke) & OMEGA (NASA)



Project Description:

- MAGIC (combining biofuel and high-value bioproducts): ALDUO hybrid system algae growth
- OMEGA (wastewater-fed freshwater algae): 110 liter floating photobioreactors (PBR) developed; scaled up to 1,600 liters

Costs:

- OMEGA (est. 204,320 floating PBRs): capital costs ($547 mill.) & revenue required ($100 mill./year)

Supporting Factors:

- DOE target of $3/gasoline gallon equivalent for algal biofuels by 2030
- $5.2 mill DOE grant (MAGIC)
- $10.8 mill feasibility study by California Energy Commission & NASA (OMEGA)

Barriers:

- OMEGA-specific: Restricted access to coastal zones (permitting issues); expensive to get wastewater; and carbon dioxide required for algae growth (algae sealed in); NASA project ended
- Algae biogas: competition with oil; scaling up

Potential Solutions:

- Use of algae for biofuel as well as other products (neutraceuticals, specialty pigments, food)