Sandia National Laboratories

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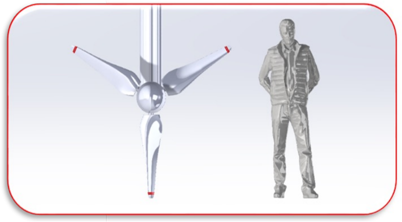
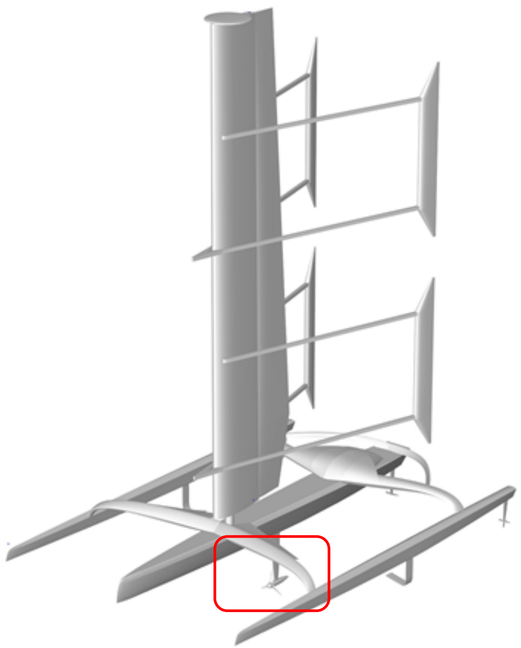
# Energy Ships, Mobile Fuel & Power Plants for Energy Security

NPS Defense Energy Seminar Series, Naval Postgraduate School


**Vincent S. Neary, Marine Energy Technologies Lead, Water Power Technologies Department**


November 15, 2022



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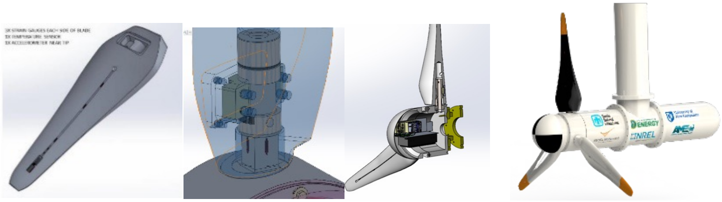
U.S. DEPARTMENT OF ENERGY

NNSA

# Marine Energy Technologies, Sandia National Labs

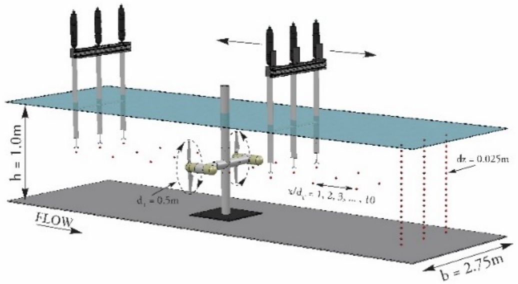
## R&D Marine Energy Technologies

Research, development, deployment and demonstration of wave, and current power generation technologies



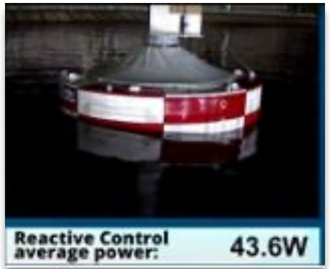
## Experimental Testing

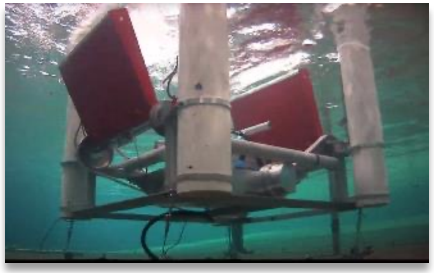
A decade of experience in hydrodynamic load measurements, and marine energy sites and laboratory testing facilities.




## Dynamics and Controls

Incorporating reactive control experts from robotics, defense, energy systems, and aerospace.



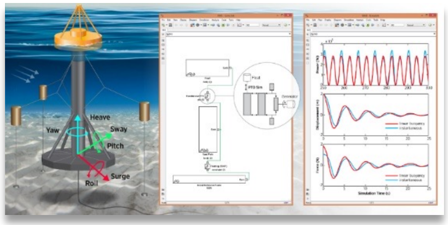



## Materials and Coatings

Prevention of corrosion & biofouling, composite performance, composite manufacturing, materials/coatings reliability.

## Code Development for Design, Optimization & Analysis

Develop and maintain open source code for marine renewable energy applications, including resource assessment, environmental effects analysis, device performance, hydrodynamic response, extreme conditions, and others.

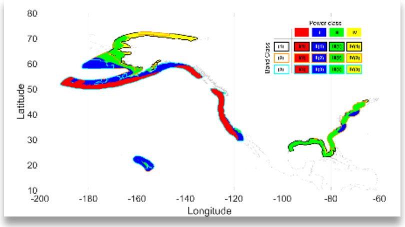


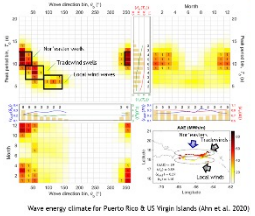

CACTUS

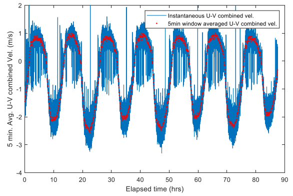
Code for Axial and Cross-flow TUrbine Simulation

## Marine Power & Load Characterization & Assessment

High-resolution hindcast modeling, methods and tools for characterizing marine power and load characteristics




## International Marine Energy Standards

Development of standards for resource characterization and assessment, device testing, power performance and design.

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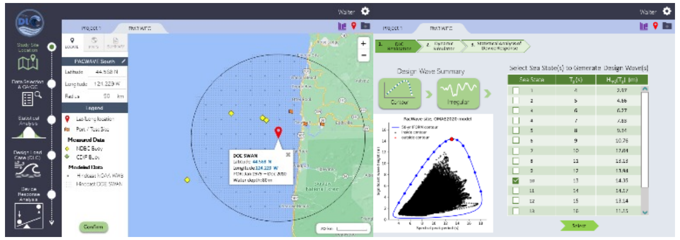
Design Load Case Generator

Graphical mapping & statistics tool to analyze design load cases for marine energy systems



# Agenda

1. Motivation for renewables, ocean wind over water
2. The energy ship concept
3. Finding early adopters
4. Scaling to bigger energy markets
5. R&D advancement, learning, cost-reduction

# Energy Security Drivers

# Climate crisis

Global warming due to dramatic increase in greenhouse gas emissions, loss of carbon sinks

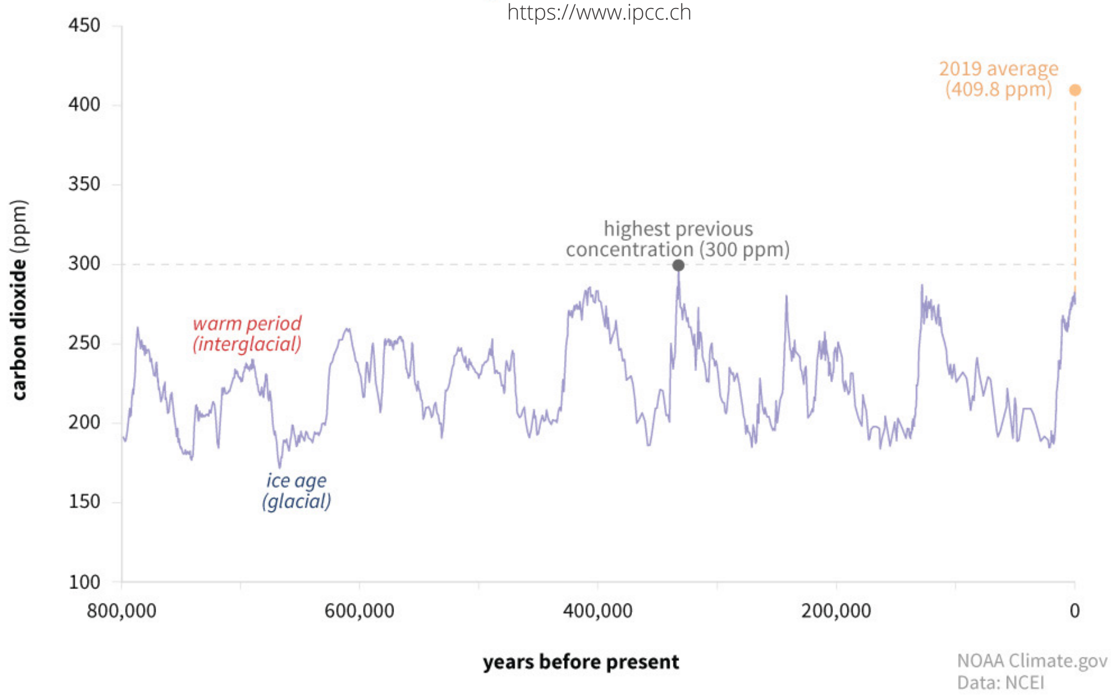
According to IPCC "model pathways," net anthropogenic $CO_2$ emissions need to decline by about 45% from 2010 levels (32.4 Gt) by 2030, reaching net zero by 2050 to prevent overshoot of +1.5°C threshold

*"Even if the recent pledges were clear and credible – and there are serious questions about some of them –we are still careening toward climate catastrophe. Our planet is talking to us. We must listen, and we must act."*

Secretary General Antonio Guterres
UN COP 26 Conference Nov 2021

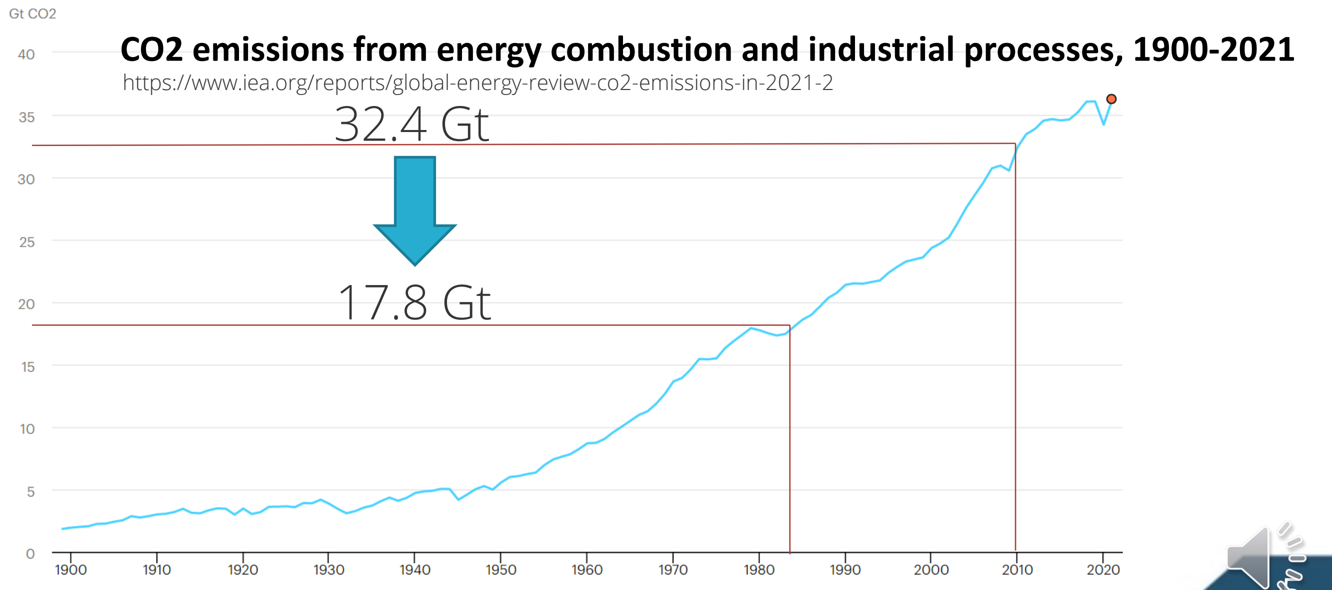
CARBON DIOXIDE OVER 800,000 YEARS

https://www.ipcc.ch



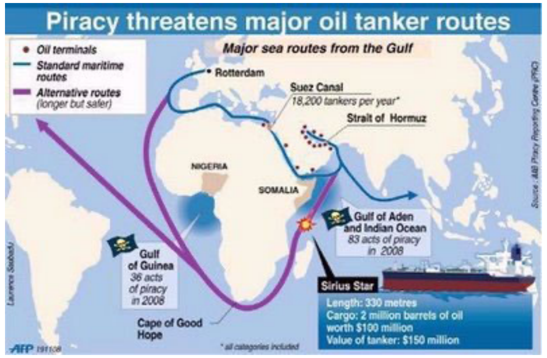

**CO2 emissions from energy combustion and industrial processes, 1900-2021**

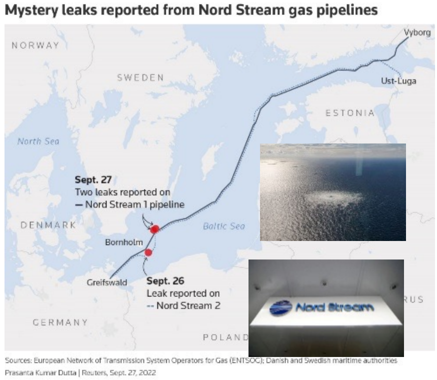
https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2



# Growing Energy Security Risks of Fossil & Nuclear Fuel Supplies

| Available | Accessible | Acceptable | Affordable |
| --- | --- | --- | --- |
| Dependence on export states<br>Vulnerable to geo-political conflict | Dependence on location<br>Dependence on service population<br>Dependence on technology | Safe, Clean, Sustainable<br>Reliable, Resilient<br>Avoid user conflicts | Competitive levelized cost of fuel<br>Price stability |





Bloomberg

**Uranium Risks Becoming the Next Critical Minerals Crisis**

It's time to lock down these resources now, before new political risks emerge.

By David Fickling
September 4, 2022 at 5:00 PM EDT

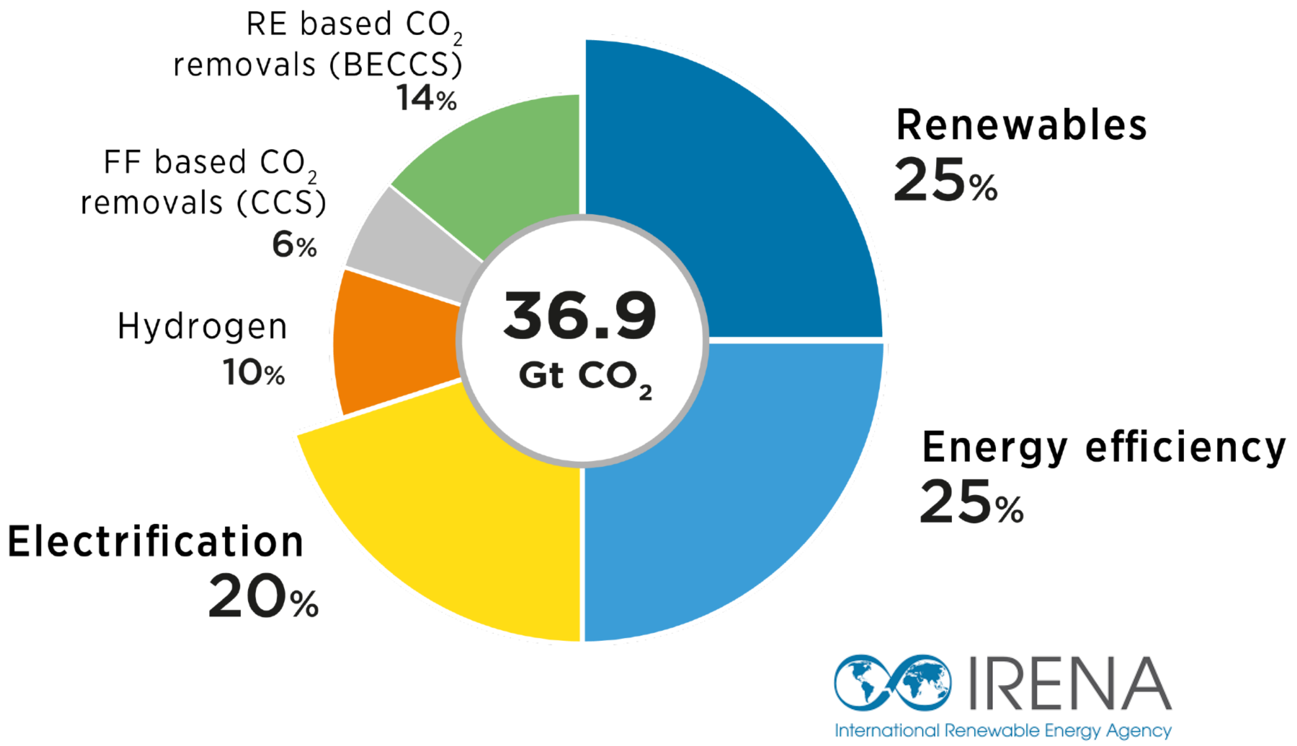
Increasing geopolitical risks & disruption to fossil fuel and uranium supplies
Overreliance on centralized power plants and oil refineries (Hurricane Maria, Puerto Rico)
Weaponization of fuels, e.g., uranium
Environmental degradation from mining, pollution, meltdown

# Energy transformation requires massive scaling renewables

Expand renewable power capacity from 2,800 gigawatts (GW) in 2020 to over 27,700 GW in 2050, 10X increase to avoid climate change, e.g., 5.5 million new 5 MW wind turbines, or 1.4 million 20 MW solar farms.

Increase in wind and solar projects would require a tenth of all the land in the contiguous US (Net-zero America project, December 2020)

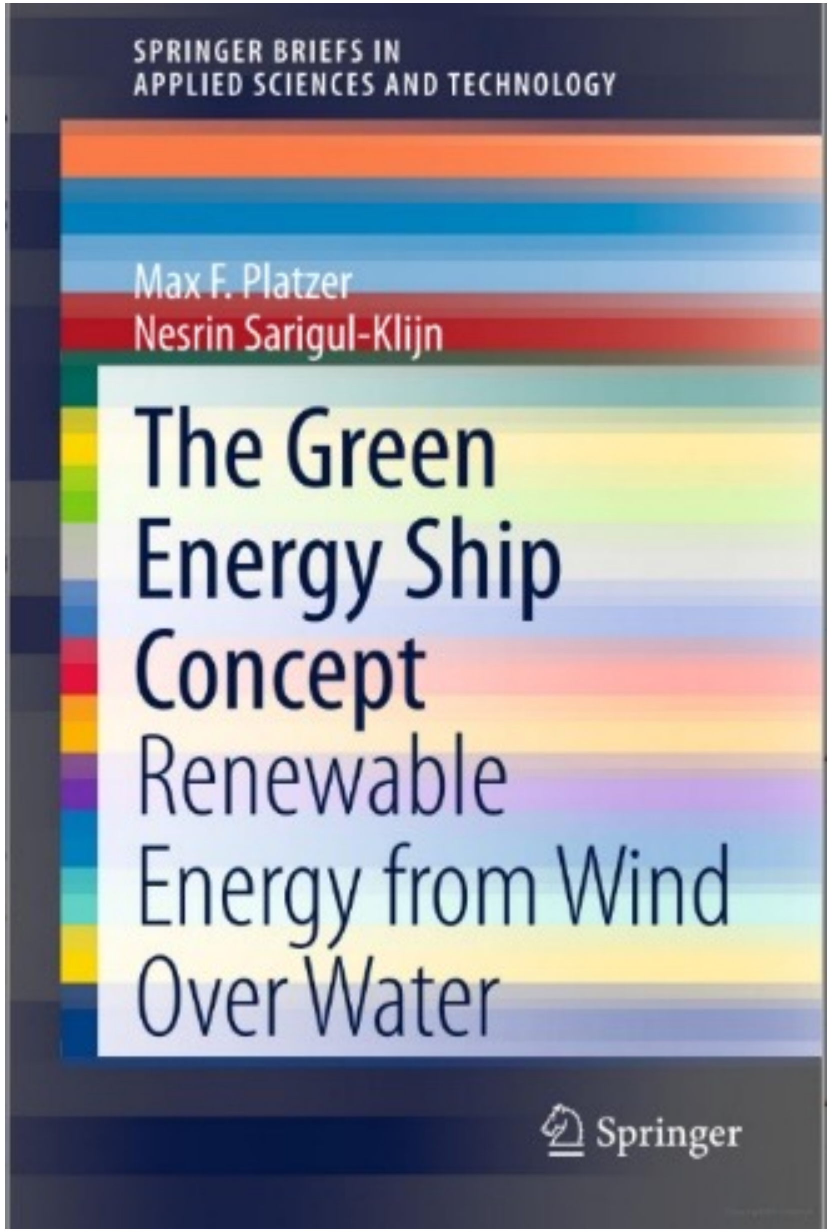
Mining of minerals and rare metals needs to increase 4X to 6X, IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, IEA, Paris https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, License: CC BY 4.0




https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook, p. 73, IRENA (2021), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi.
https://cmi.princeton.edu/annual-meetings/annual-reports/year-2019/the-net-zero-america-project-finding-pathways-to-a-carbon-neutral-future/

# Energy Ship Concept – Mobile Renewable Power Generation & Diverse Power/Fuel Supply

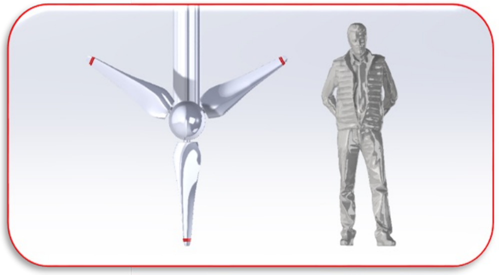
# The Energy (E) Ship concept

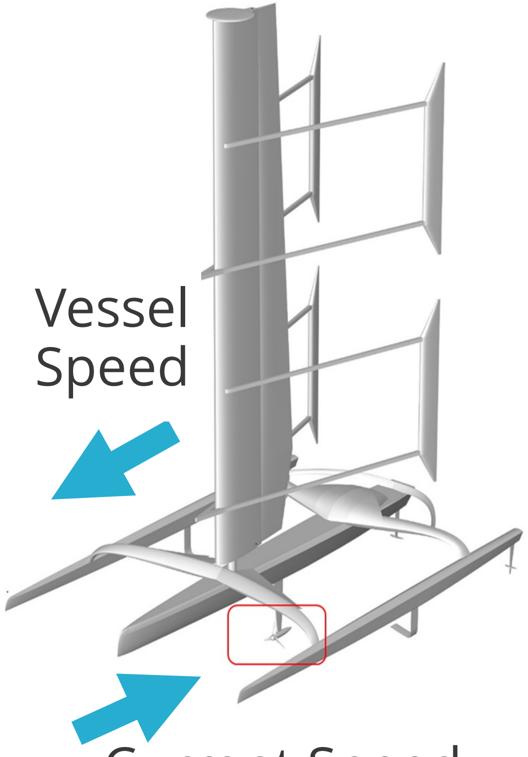



An autonomous sailing ship that uses wind-propulsion to drive a hydrokinetic turbine that recharges banks of electric batteries or powers fuel manufacturing and storage

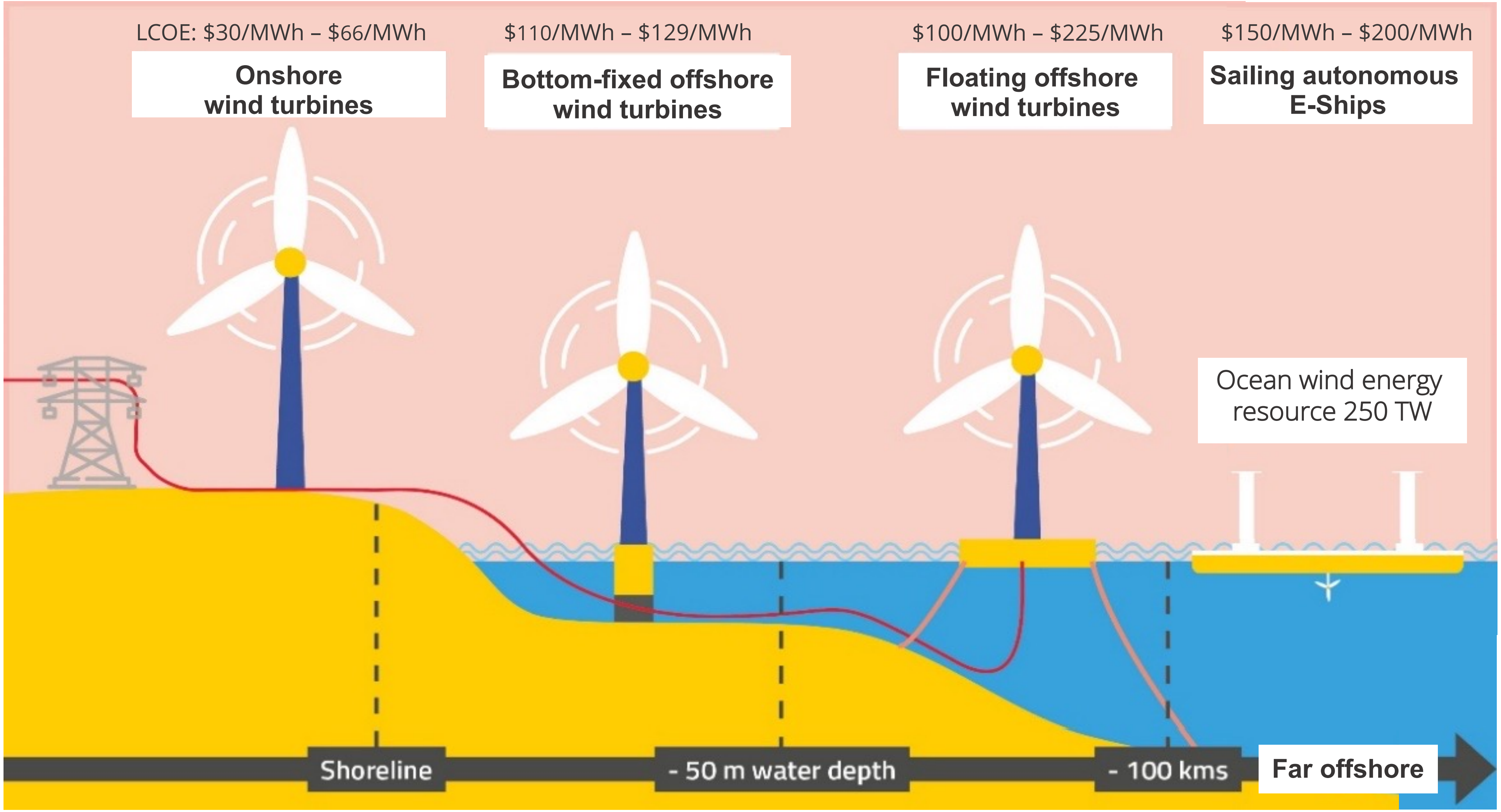
M.F. Platzer and N. Sarigul-Klijn, The Green Energy Ship Concept: Renewable Energy from Wind over Water, Springer Briefs in Applied Sciences and Technology, Springer ©2021

First proposed in 2009 by M.F. Platzer and N. Sarigul-Klijn at the ASME Energy Sustainability Conference, San Francisco and received ASME Energy Division Best Paper Award.





# Logical next step: Ocean wind energy, mobile energy generation platforms – Energy Ships



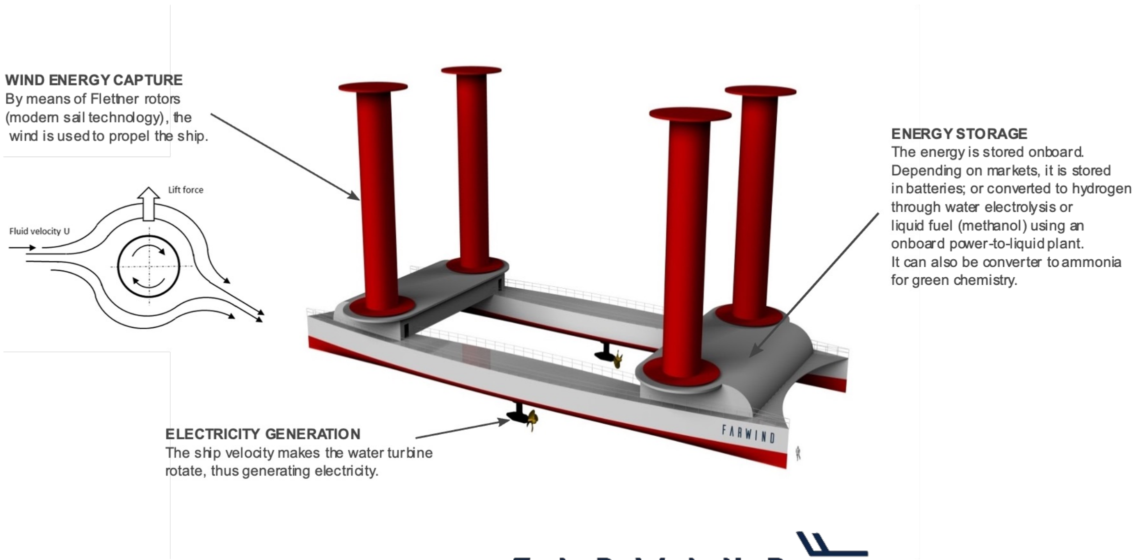

Positioning of far-offshore wind energy conversion. © Charlotte Ruel – Ecole Centrale de Nantes

# E-Ship concepts

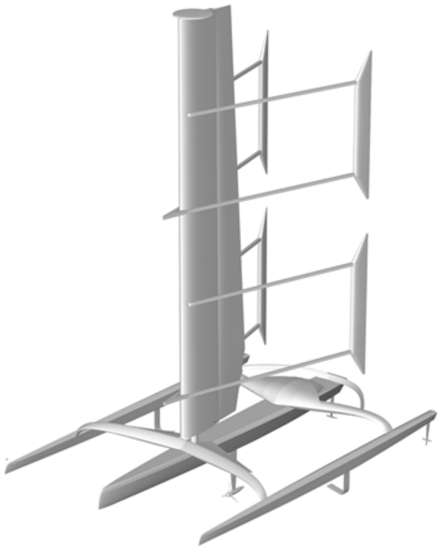
Ouchi & Henzie (2017)

University of Tokyo/ Mitsui O.S.K Lines

DRIFT ENERGY LTD, UK




FARWIND, France



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Renewable Energy Technologies
https://energy.sandia.gov

*Green Energy Ship LLC*, USA

# The Energy Ship – Key attributes

**MORE POWER**

Scalable to satisfy the global energy demand (up to 30 MW per ship, millions of ships)

Windsail power significantly increases hydrokinetic turbine inflow speeds between 5 to 15 m/s

**MORE OF THE TIME**

Mobility provides high capacity factors, 70-80% avoids hazards, and reduces market barriers and costs

**IN MORE PLACES**

Oceans with steady powerful tradewinds cover 72% of the globe, with no exclusion zones or "land-use" constraints

**MORE QUICKLY**

Operation in high seas (international waters) avoids extensive and costly project permitting process & NIMBY resistance causing extensive delays

Most subsystems at TRL 9

**MORE ACCEPTABLE**

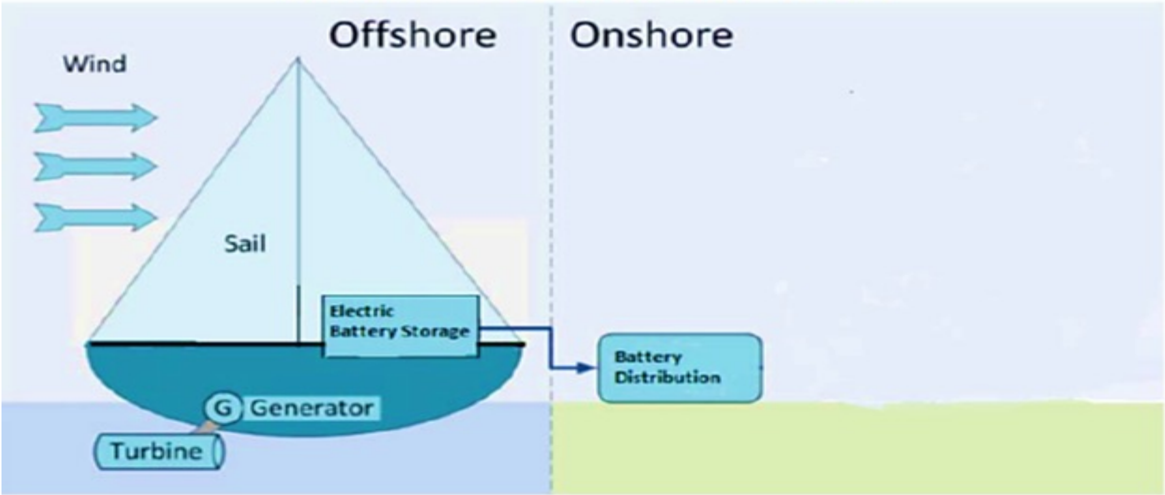
Autonomous system reduces safety risks and operational costs

Relatively minimal environmental impacts with autonomous collision avoidance systems

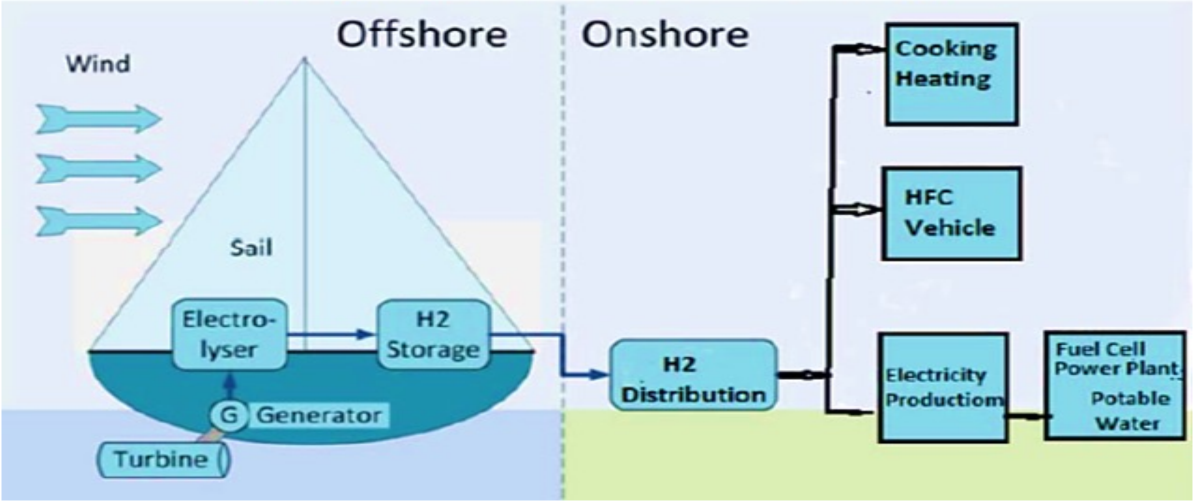
**VERSATILE**

A variety of energy storage options, e.g., battery-stored electrical energy, sustainable liquid fuels, compressed or liquefied hydrogen

(a) Electric Battery Energy Storage




(b) Hydrogen Production and Delivery

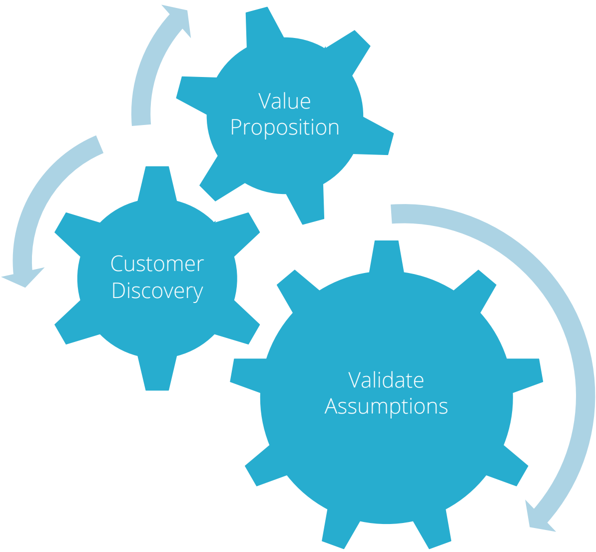


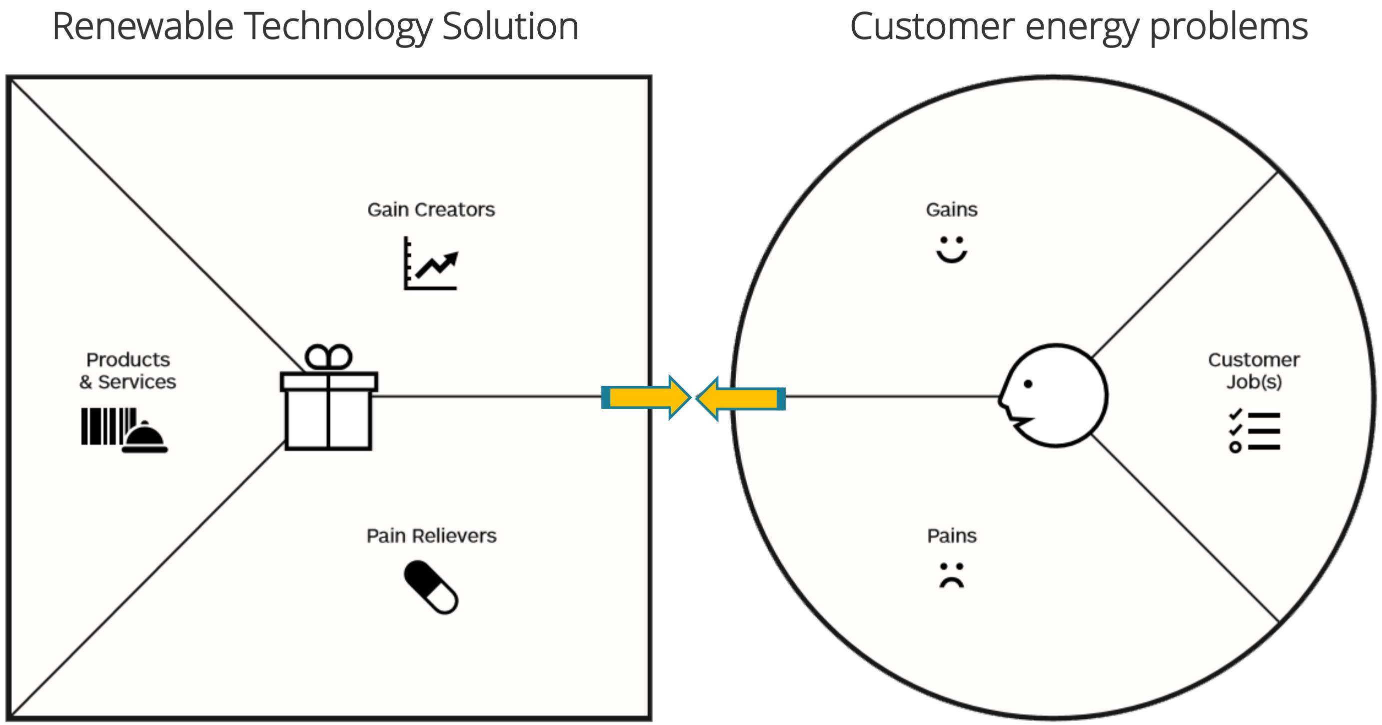
# Commercialization Planning

# How do we advance nascent renewable energy technologies to commercialization?

Key initiative of Office of Technology Transitions (OTT), where researchers and industry mentors define technology value propositions, conduct stakeholder discovery interviews, and develop viable market pathways for their technologies.

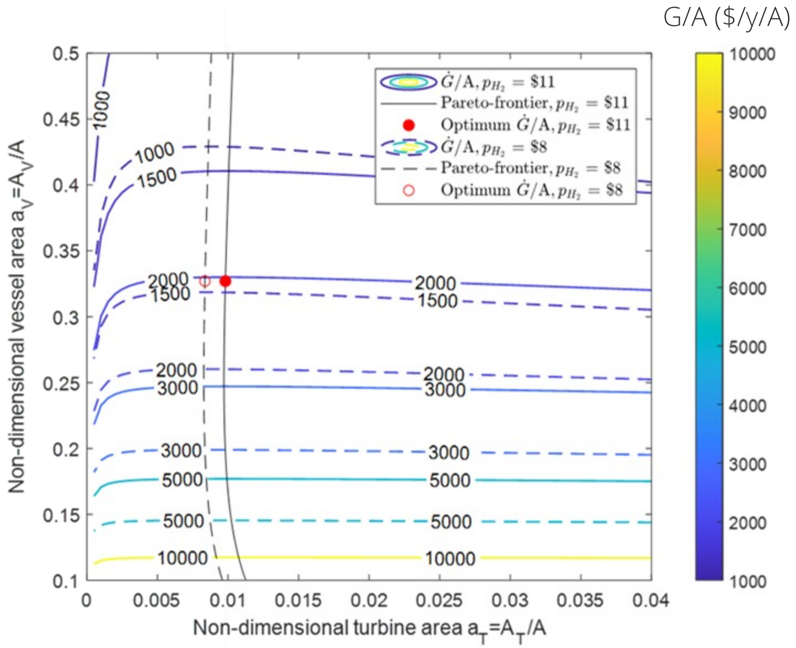
Researchers return to the lab with a framework for industry engagement to guide future research and inform a culture of market awareness within the labs.



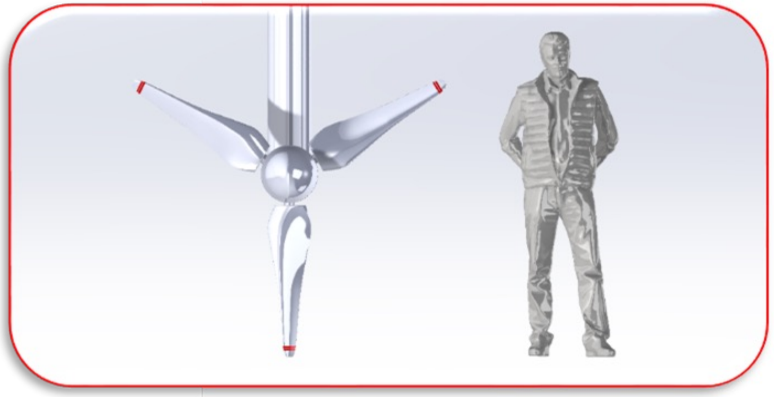




ENERGY I-CORPS
U.S. Department Of Energy

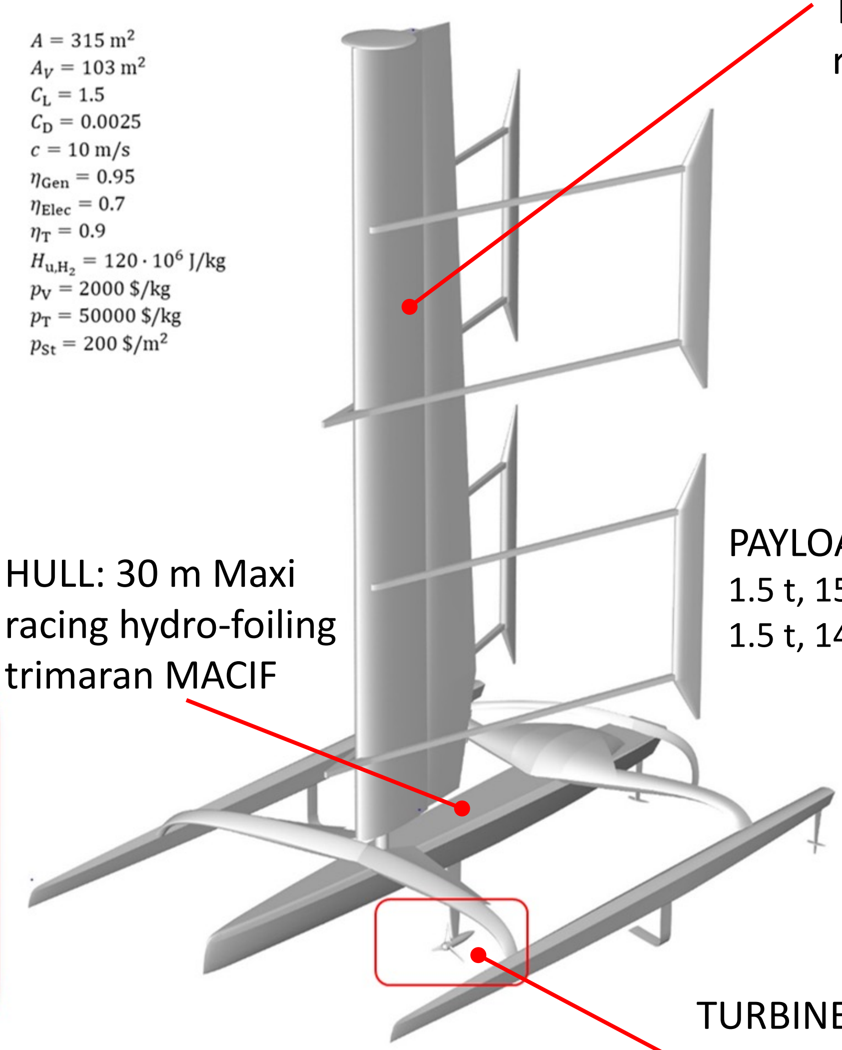
# 350 kW Hydro-foiling E-Ship Concept Design (TRL 2-3)




$A = 315\ \text{m}^2$
$A_V = 103\ \text{m}^2$
$C_L = 1.5$
$C_D = 0.0025$
$c = 10\ \text{m/s}$
$\eta_{Gen} = 0.95$
$\eta_{Elec} = 0.7$
$\eta_T = 0.9$
$H_{u,H_2} = 120 \cdot 10^6\ \text{J/kg}$
$p_V = 2000\ \$/\text{kg}$
$p_T = 50000\ \$/\text{kg}$
$p_{St} = 200\ \$/\text{m}^2$



SAIL: 315 m$^2$ Harborwing Technologies HWT-X3 rigid wing sail



HULL: 30 m Maxi racing hydro-foiling trimaran MACIF

PAYLOAD OPTIONS (1500 kg):
1.5 t, 15 m$^3$ LH2 tanks, 35,500 kWh
1.5 t, 14-13.5 kWh Tesla PW2, 189 kWh

TURBINE: 2 m, 350 kW MHKF1 turbine system

# Value Proposition

**Supply distributed off-grid green energy from ocean wind for remote power at sea and for disaster recovery for isolated communities**

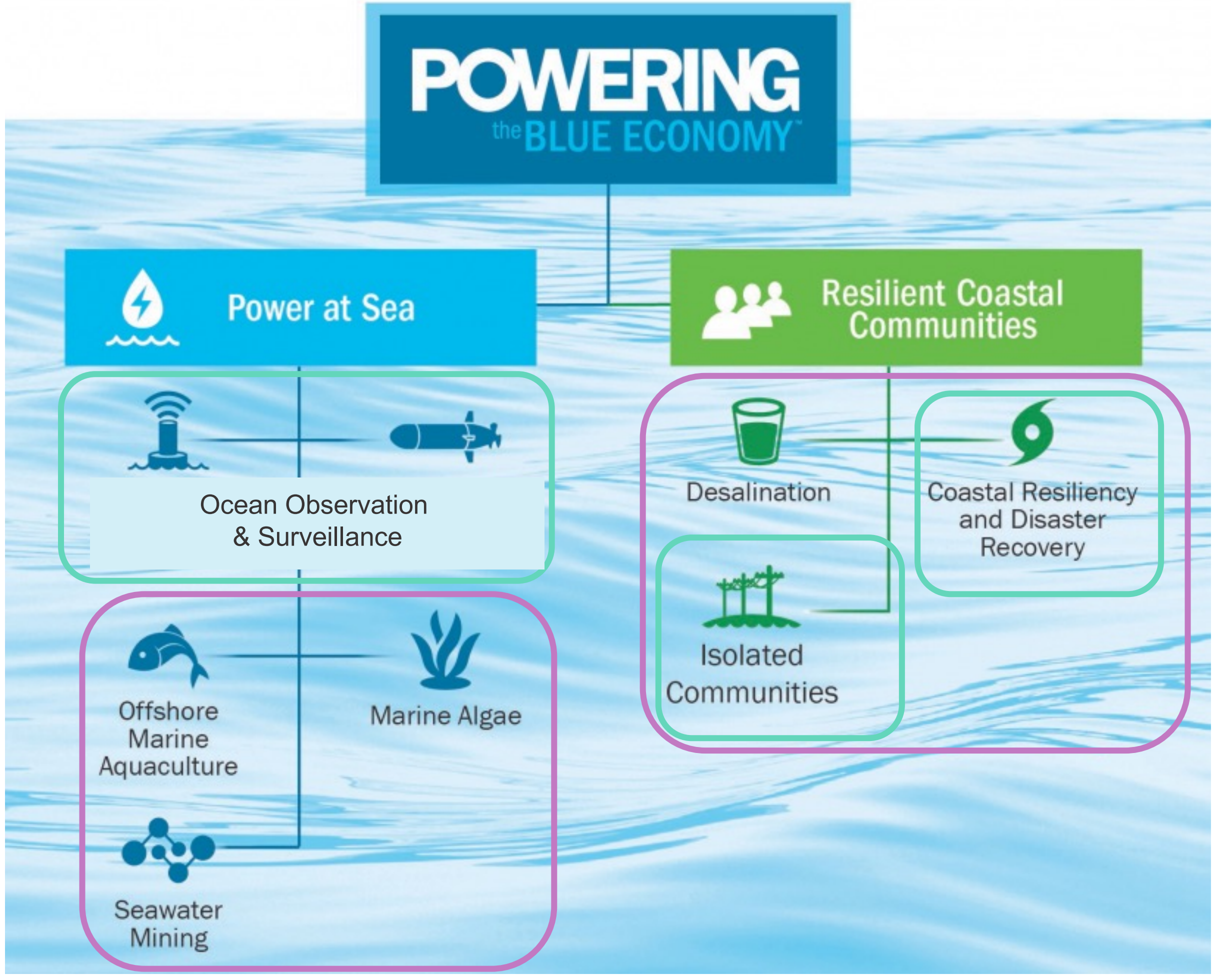
**Stable Unlimited Supply from Ocean Wind Energy** and **Mobile, Diverse Fuels, Flexible Distribution, On-Demand Access, Anywhere, Anytime**

- **Sustainable Decarbonization**
- **Stable Fuel Costs**
- **Secure Fuel Supply**

# The Blue Economy – Customer Segments

**Beachhead (Early-Adopters):** Battery Charging Small Power Demands

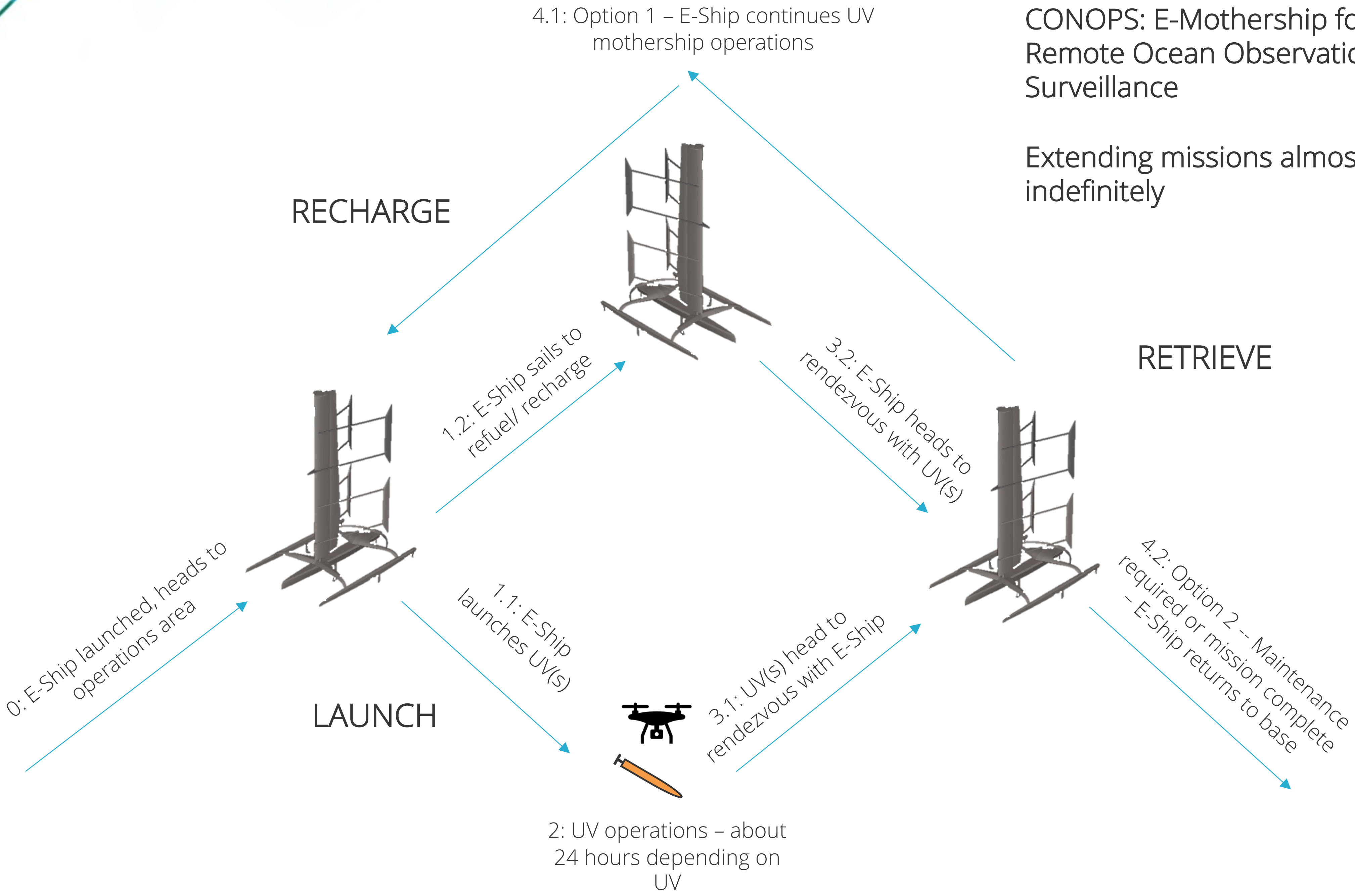
**Future Markets**: Zero-emission Fuels for Mid- to High-Power Demands



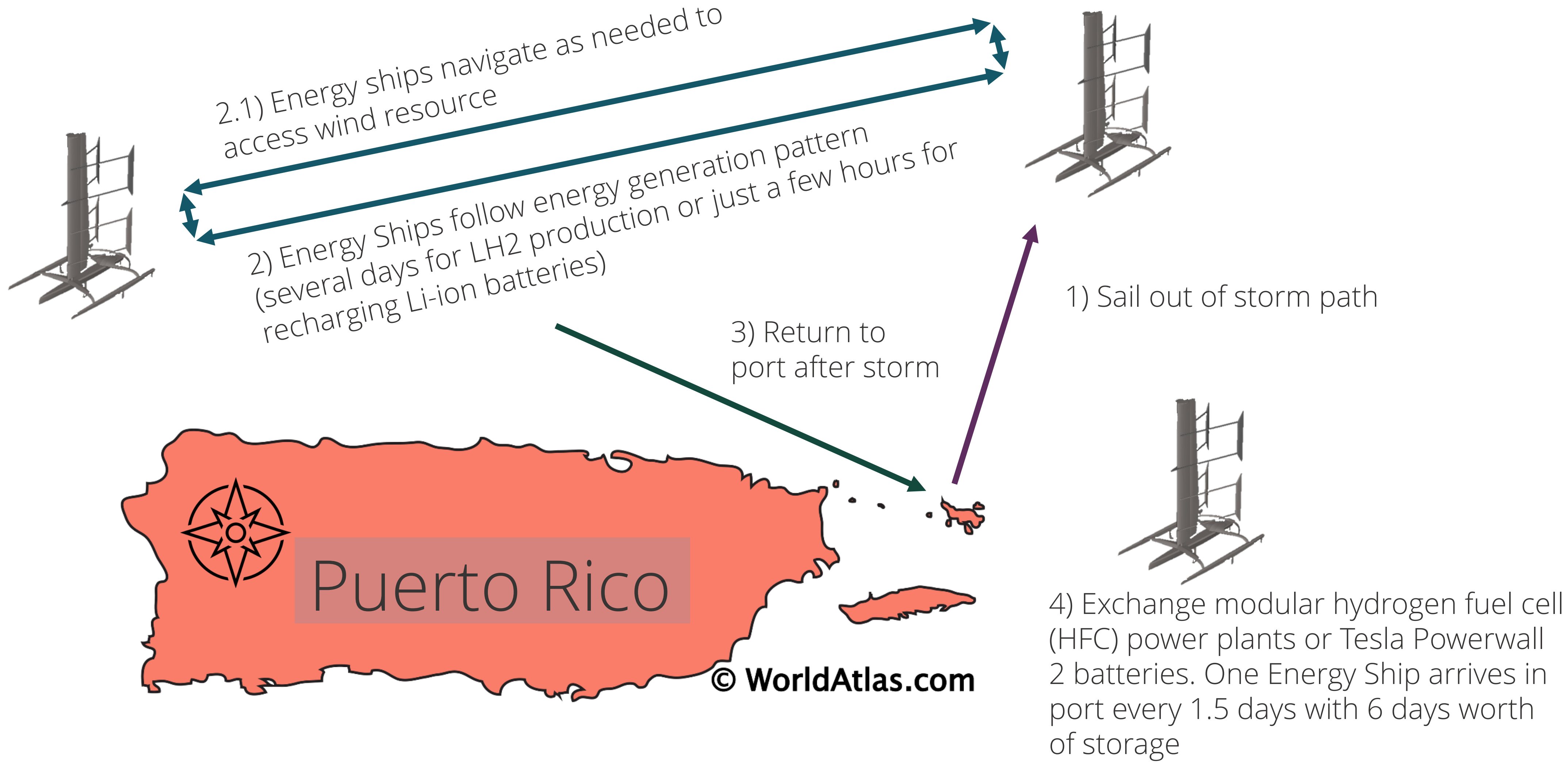

Source: U.S. DOE Water Power Technologies Office

# CONOPS: E-Mothership for Remote Ocean Observations & Surveillance

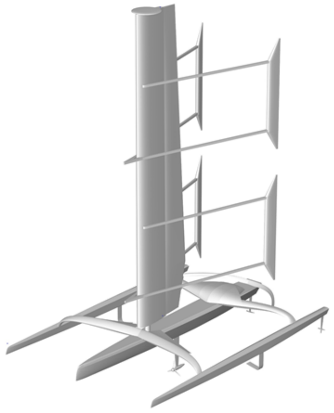
## Extending missions almost indefinitely



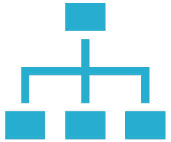
# CONOPS: Supplying power plants for disaster recovery



# Revenue Potential



## Revenue Stream 1

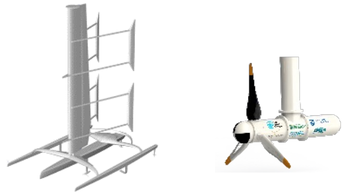


***Licensing***

*Licensing technology to defense contractors or ship builders.*

*Licensor*

## Revenue Stream 2



***Equipment Sales***

*Building and then selling energy ships or components. Revenue derived from 1 time sale.*

*Manufacturer*

## Revenue Stream 3

***Fuel Sales***

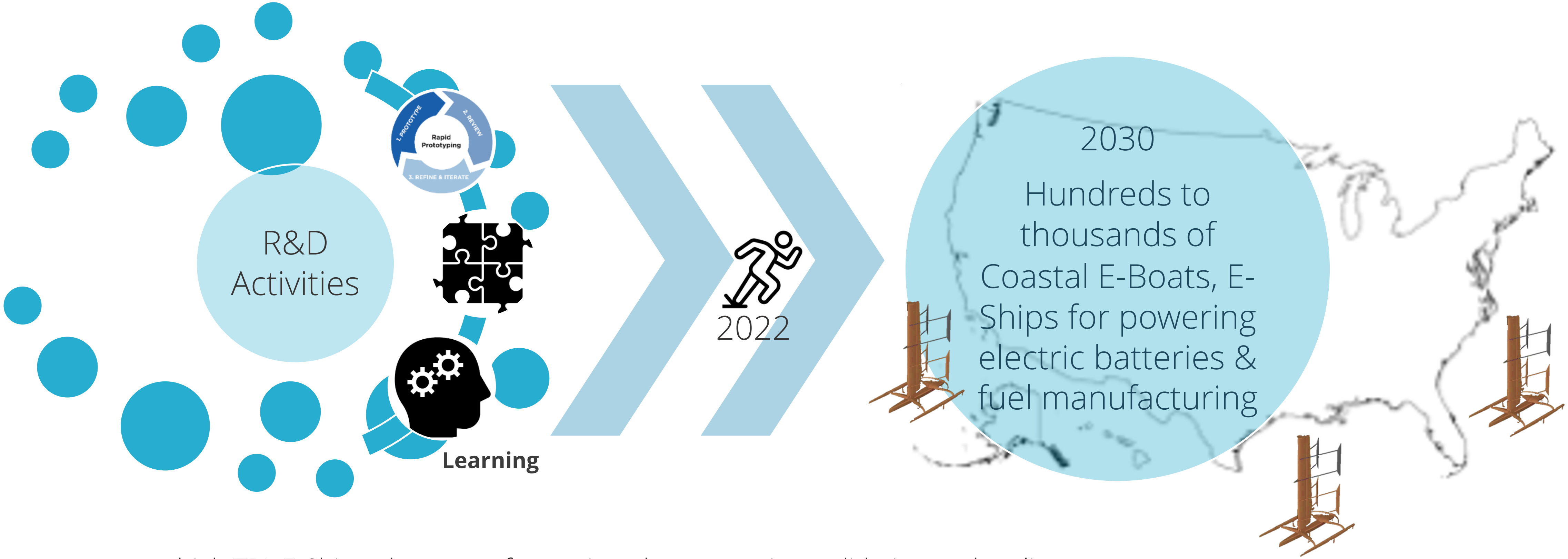
*5-10 year contract offering refueling* services at set price.*

**hydrogen or electrons*

*Owner*

# Scaling to bigger energy markets

# Two-phase commercialization strategy: Phase 1, 0.3-0.5 MW Coastal E-Boats, 0.5-1 MW E-Ships for Alternative Early-Adopter Markets



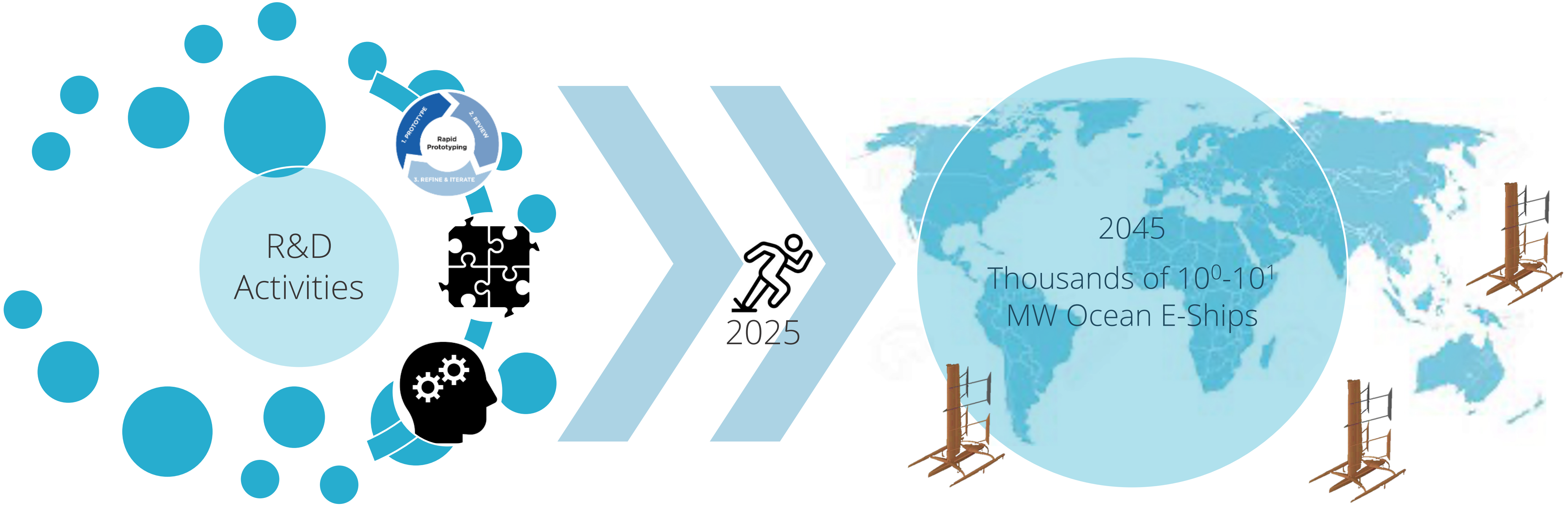

Rapidly integrates most high TRL E-Ship subsystems for testing, demonstration, validation and scaling

Allows early learning of deployment, operation & maintenance and decommissioning (DO&MD)

Saves complex fuel manufacturing and storage subsystems for Phase 2

Early commercialization for early adopter, high-cost energy markets, e.g., superyachts, ferries

# Two-phase commercialization strategy: Phase 2, 1-10 MW Ocean E-Ships for Utility-Scale Energy Markets (Electricity, Transportation, Heating, Heavy Industry)

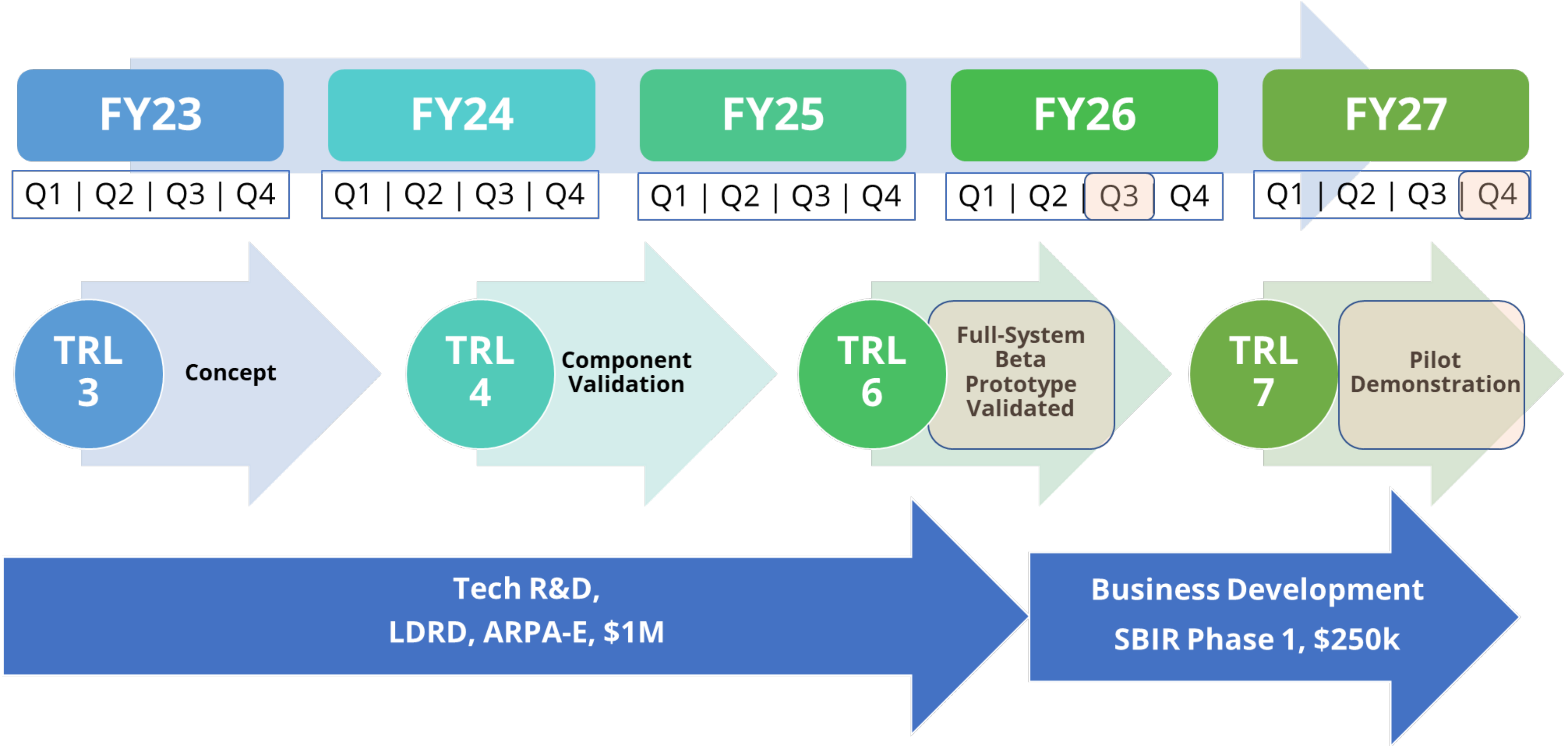



<u>Disaggregate Tasks to Three Vessels?</u>

Energy Conversion & Storage Ship → Fuel Manufacturing Plant Ship → Fuel Tanker Transport Ship

# R&D Advancement

# R&D Roadmap, Next Steps




## Other Next Steps:

- Continue customer discovery process & milestone mapping (Ongoing)
- Continue to use tools provided in Energy I-Corps (Ongoing)
- Raising additional R&D funds

# Design Tradespace Optimization Model (Existing)

## Inputs

### Hydro/Aerodynamic Parameters

- $c$: inflow wind speed
- $C_D$: vessel drag coefficient
- $A_V$: vessel surface area
- $C_L$: sail lift coefficient
- $A$: sail area
- $\rho_l$: water density
- $\rho_g$: air density

### Mechanical/Physical Parameters

- $\eta_T$: turbine efficiency factor
- $\eta_{Gen}$: generator efficiency factor
- $\eta_{Elec}$: electrolyzer efficiency factor
- $H_{u,H_2}$: caloric value of hydrogen

### Economic Parameters

- $P_V$:vessel cost/area
- $P_T$: turbine cost/swept area
- $P_{ST}$: storage cost/sail area
- $P_{H_2}$: hydrogen price/kg
- $i$: Rate of interest, %
- $n$: number of annuities

## Economic Optimization

### Performance Optimization

#### Vessel Propulsion

Vessel drag

$$W = A_V C_D V^2 \rho_l / 2$$

Sail thrust

$$T = \sin\beta \cdot \frac{\rho_g}{2} A C_L(\alpha) w^2$$

Force balance

$$T = W + W_T$$

$$V(\alpha_0, \beta)$$

#### Hydrokinetic Turbine

Turbine drag

$$W_T = \Delta p A_T$$

$$\Delta p = V_{in}^2 (1 - \zeta^2) \rho_l / 2$$

$$\zeta = V_{out} / V_{in}$$

$$\zeta(\alpha_0, \beta, C_L, C_D, A_V, A_T, V)$$

Turbine performance

$$C_P = P_S / P_{avail}$$

$$P_S = \eta_T \Delta p A_T \bar{V}$$

$$\bar{V} = (V_{in} + V_{out})/2$$

$$P_{avail} = \rho_g c^3 A / 2$$

$$C_P(A_T)$$

#### Energy Storage

Investment costs

$$\dot{C} = CRF\,(A_V P_V + A_T P_T + A P_{st})$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Revenue

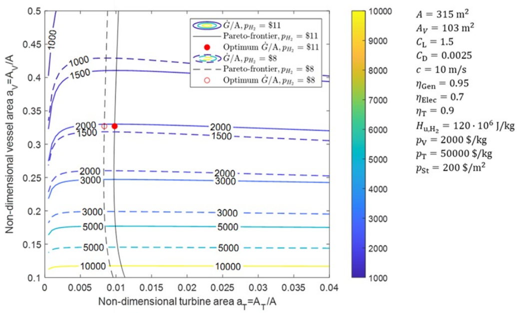
$$\dot{R} = \frac{\rho_g}{2 H_{u,H_2}} c^3 A C_P \eta_{Gen} \eta_{Elec} P_{H_2}$$

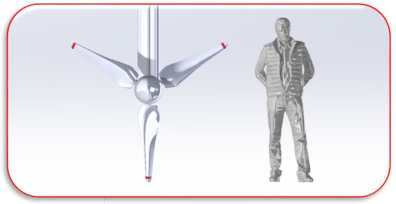
where,
- $V$: vessel speed (= $V_{in}$, inflow speed to turbine)
- $w$: relative wind speed
- $\alpha$: angle of attack
- $\beta$: relative wind direction
- $\zeta$: axial velocity ratio
- $P_S$: mechanical turbine shaft power
- $P_{avail}$: available power

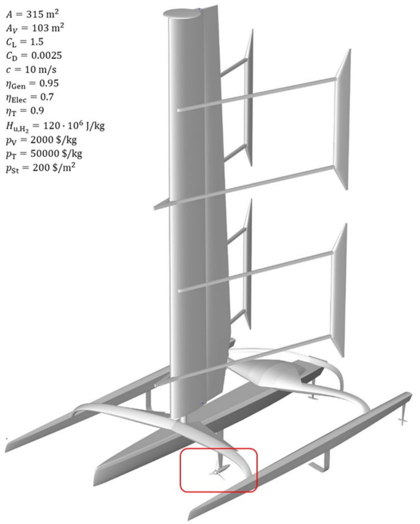
**Levelized Cost of Fuel (LCOF)**

**Economic Profit, $\dot{G} = \dot{R} - \dot{C}$**

**Optimum Turbine Area, $A_{T,opt}$**





# Design Tradespace Optimization Model (Upgrades)

**Inputs**

**Hydro/Aerodynamic Parameters**

- $c$: inflow wind speed
- $C_{\mathrm{D,hydro,V}}$: hydrodynamic vessel drag coefficient database
- $C_{\mathrm{D,aero,V}}$: aerodynamic vessel drag coefficient database
- $A_{\mathrm{V}}$: vessel surface area
- $C_{\mathrm{L,S}}$: sail lift coefficient database
- $A$: sail area
- $\rho_l$: water density
- $\rho_g$: air density
- $C_{\mathrm{D,AF}}$ : airfoil section drag coefficient database
- $C_{\mathrm{L,AF}}$: airfoil section lift coefficient database
- $C_{\mathrm{D,HF}}$ : Hydrofoil drag coefficient database
- $C_{\mathrm{L,HF}}$: Hydrofoil lift coefficient database
- $A_{\mathrm{HF}}$: hydrofoil surface area

**Design Parameters**

- Airfoil type
- Hydrofoil geometry
- Sail type and geometry
- Initial turbine design
- Number of airfoil sections for turbine blade

**Mechanical/Physical Parameters**

- $\eta_{\mathrm{T}}$: turbine efficiency factor
- $\eta_{\mathrm{Gen}}$: generator efficiency factor
- $\eta_{\mathrm{Elec}}$: electrolyzer efficiency factor
- $H_{\mathrm{u,H_2}}$: caloric value of hydrogen

**Economic Parameters**

- $P_{\mathrm{V}}$:vessel cost/area
- $P_{\mathrm{T}}$: turbine cost/swept area
- $P_{\mathrm{ST}}$: storage cost/sail area
- $P_{\mathrm{H_2}}$: hydrogen price/kg
- $i$: Rate of interest, %
- $n_a$: number of annuities
- $P_{\mathrm{S}}$: sail cost/area
- $P_{\mathrm{HF}}$: hydrofoil cost/area

**Economic Optimization**

**Performance Optimization**

**Vessel Propulsion**

Vessel drag

**Look up in database**

$C_{\mathrm{D,hydro,V}}(Re_{\mathrm{LOA}}, \theta_t, s)$
$C_{\mathrm{D,aero,V}}(Re_{\mathrm{LOA}}, \theta_t, s)$

**or**

**Empirical methods**

$W = A_{\mathrm{V}} C_{\mathrm{D}} V^2 \rho_l / 2$

Sail thrust

**Look up in database**

$C_{\mathrm{L,S}}(Re_{\mathrm{chrd}}, \alpha)$

**or**

**Empirical methods**

$T = \sin\beta \cdot \frac{\rho_g}{2} A C_{\mathrm{L,F}}(Re_{\mathrm{chrd}}, \alpha) w^2$

**Hydrofoil**

Hydrofoil drag and lift

**Look up in database**

$C_{\mathrm{D,HF}}(Re_{\mathrm{chrd}}, \theta_t, s)$
$C_{\mathrm{L,HF}}(Re_{\mathrm{chrd}}, \theta_t, s)$

**or**

**Blade Element Momentum Theory (BEMT)/Vortex-Lattice Model**

**Hydrokinetic Turbine Design Optimization**

**Blade Element Momentum Theory (BEMT) Model**

**Combined Extended Analytical Betz-Schmidt Method**

**and**

**Turbine Design Optimization Module**

$C_P$

**Vessel-Hydrofoil Dynamic Stability Analysis Module**

**Turbine Layout Analysis Module**

Optimized $V$ at force balance
$T = W + W_{\mathrm{HF}} + N_T \cdot W_T$

**Energy Storage**

Investment costs

$\dot{C} = CRF\,(A_{\mathrm{V}} P_{\mathrm{V}} + A_{\mathrm{T}} P_{\mathrm{T}} + AP_{\mathrm{st}} + AP_{\mathrm{S}} + A_{\mathrm{HF}} P_{\mathrm{HF}})$

$CRF = \frac{i(1+i)^{n_a}}{(1+i)^{n_a} - 1}$

Revenue

$\dot{R} = N_T \frac{\rho_g}{2 H_{\mathrm{u,H_2}}} c^3 A C_{\mathrm{P}} \eta_{\mathrm{Gen}} \eta_{\mathrm{Elec}} \lambda_{\mathrm{inter}} P_{\mathrm{H_2}}$

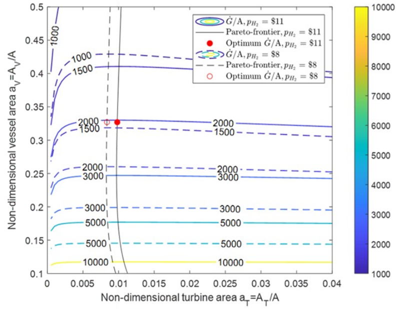
where,
- $V$: vessel speed (=$V_{\mathrm{in}}$, inflow speed to turbine)
- $w$: relative wind speed
- $\alpha$: angle of attack
- $\beta$: relative wind direction
- $\zeta$: axial velocity ratio
- $P_{\mathrm{S}}$: mechanical turbine shaft power
- $P_{\mathrm{avail}}$: available power
- $\theta_t$: trim angle of vessel
- $s$: sinkage of vessel
- $N_T$: number of turbines
- $\lambda_{\mathrm{inter}}$: loss factor due to interaction between turbines

**Levelized Cost of Fuel (LCOF)**

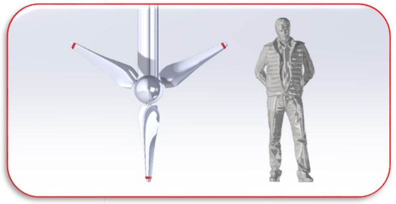
**Economic Profit, $\dot{G} = \dot{R} - \dot{C}$**

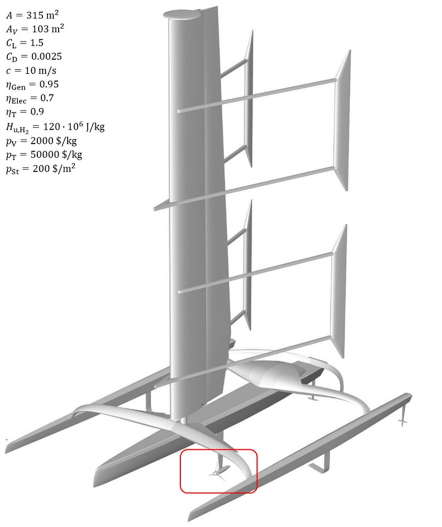
**Optimum Turbine Design**

**Number of Turbines**

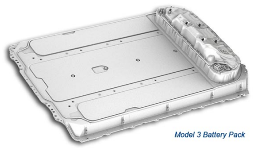



$A = 315\ \mathrm{m}^2$
$A_V = 103\ \mathrm{m}^2$
$C_{\mathrm{L}} = 1.5$
$C_{\mathrm{D}} = 0.0025$
$c = 10\ \mathrm{m/s}$
$\eta_{\mathrm{Gen}} = 0.95$
$\eta_{\mathrm{Elec}} = 0.7$
$\eta_{\mathrm{T}} = 0.9$
$H_{\mathrm{u,H_2}} = 120 \cdot 10^6\ \mathrm{J/kg}$
$p_{\mathrm{V}} = 2000\ \$/\mathrm{kg}$
$p_{\mathrm{T}} = 50000\ \$/\mathrm{kg}$
$p_{\mathrm{St}} = 200\ \$/\mathrm{m}^2$

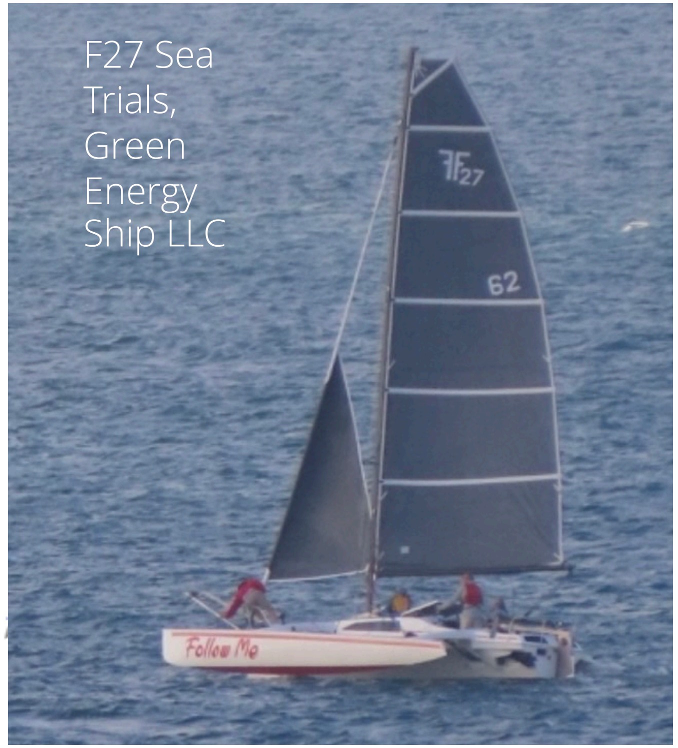




# Performance demonstration & assessment




Lithium-ion battery

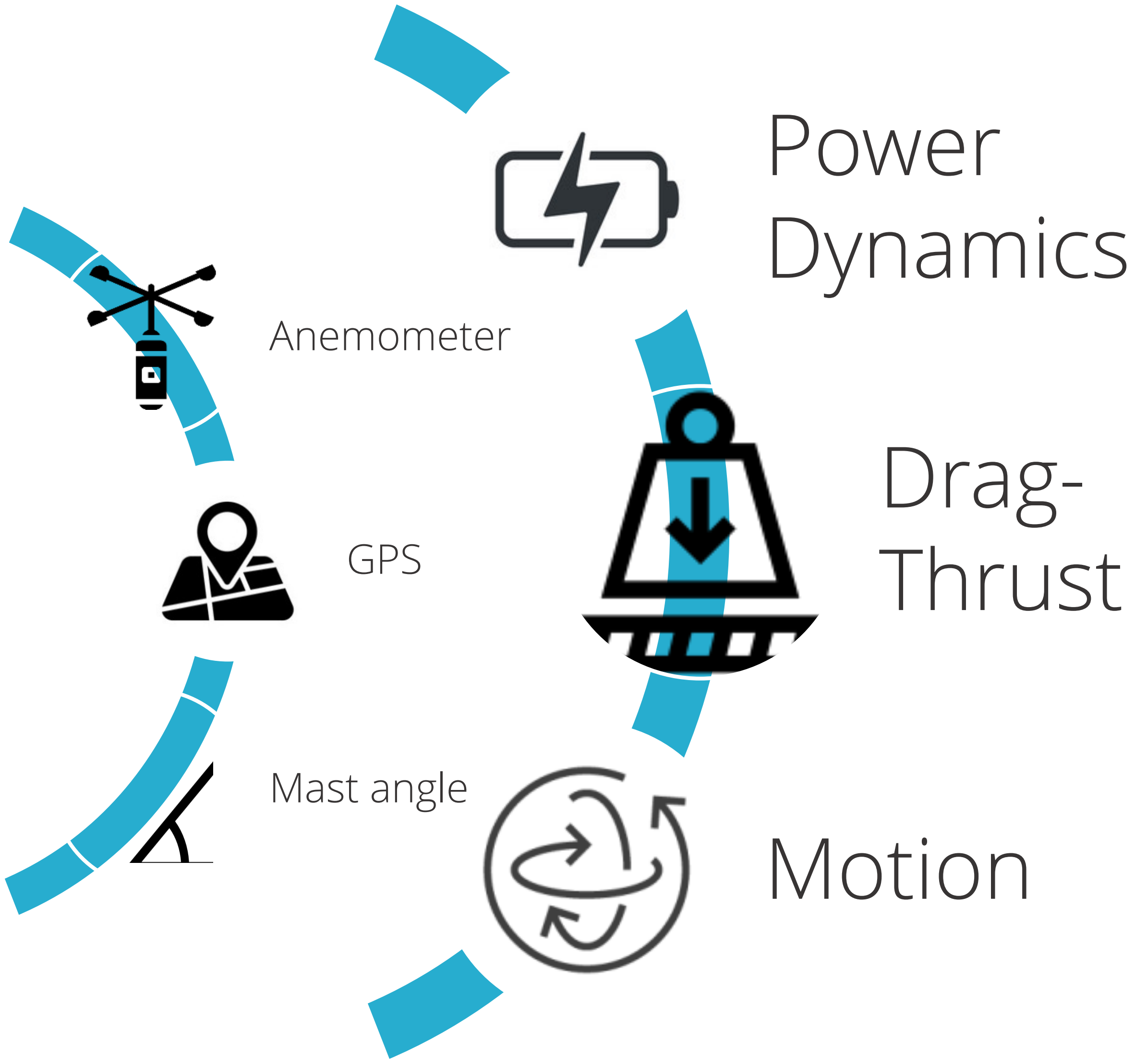



600 W, Watt & Sea hydrokinetic turbine generator

350 kW, USDOE MHKF1 turbine

or

SIT Schottel turbine



# Main takeaways

- Ocean wind energy – Energy Ships needed for rapid transition to renewables
- Learning in early adopter markets main driver to increase techno-economic performance
  - Motherships for deploying, retrieving, recharging & refueling uncrewed vehicles
  - Powering remote islands and bases, battle groups to untether logistics tails, especially during conflicts, wars, and natural disasters

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# THANK YOU

Questions? Comments?

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# Parting thoughts …

Could the US Navy be the pioneer and global leader of large-scale conversion of ocean wind power into renewable fuels?

Will UN Secretary Guterres' warning finally trigger a similar technical response as occurred in the WWI and WWII crises?

It took only 15 years to expand the production of airplanes from one in 1903 to well over 200,000 by the end of World War I

It took only 15 years from the production of the first jet-propelled aircraft in 1939 and of the first rocket in 1942 to start commercial jet travel in 1952 and spaceflight in 1957