Lecture - Handbook of Ocean Wave Energy

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CONTENTS

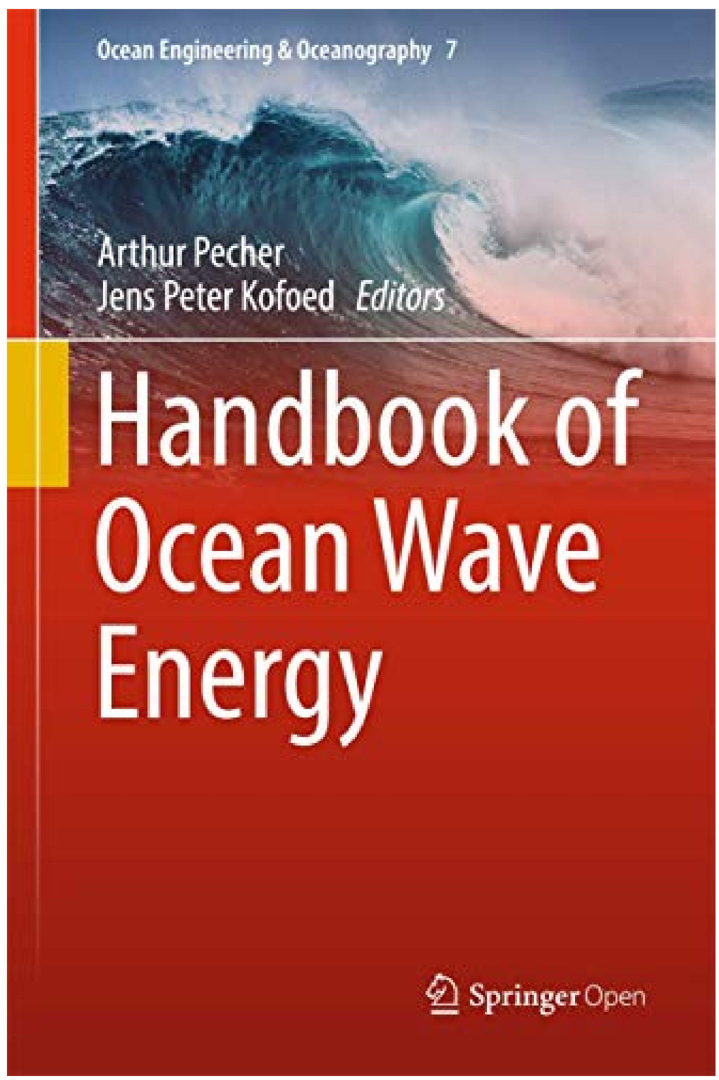
September 1, 2024

In the Spring of 2024, the Hawaii Natural Energy Institute (HNEI) received Federal funding from the US Department of Energy to rekindle operational capacity of the Hawaii Marine Energy Center (HMEC). As "Director of Outreach", my goal is to increase awareness of ocean energy activities and opportunities here in Hawaii, as well as the US Affiliated Pacific Islands (USAPI). Although most outreach communications will take place on HMEC's website, it is not the best platform to serve STEM content.

In the Spring of 2025, a close friend and colleague of mine, Professor Jacob Tyler, and I will be running a semester long course at Kapiolani Community College (KCC) here on Oahu, Hawaii. As per the curriculum requirements, the course fundamentally serves as an introduction to engineering and design. However, uniquely different from a conventional engineering course, the application focus will be on ocean wave energy converters. Growing up on an island in the Pacific, many kids are already highly familiar with, at least in an intuitive sense, the ocean environment. Thus, it makes perfect sense to pull this love for the ocean into the classroom and expose students early on to a growing ocean energy sector.

The semester long course will be broken up into three main sections: 1) a high level introduction of ocean wave energy to facilitate project research and foster ideas, 2) a practical introduction to computer-aided design (CAD) and added manufacturing via fused deposition modeling (FDM), and 3) experimental testing of a scaled model, including data acquisition and post test analysis. Students will then be asked to create a project poster and present at the Student Undergraduate Research Fair (SURF). The complete course Syllabus can be downloaded here.

The required only required text for this course, shown to the right, is an open access book titled "Handbook of Ocean Wave Energy" published by Springer (source). In the even the link fails, I've provided a copy of the book `here` for your convenience. Drawing from select chapters, the intent of this Jupyter Book is to facilitate the introductory lecture series.



A PDF copy of this presentation can also be `downloaded` free of charge for you to view offline.

> **Warning**
>
> Being the first time we're teaching this course, the material is subject to change and will be molded to fit course outcomes.

CHAPTER ONE

CHAPTER 1: INTRODUCTION

Representing HMEC, I've tried to place the lecture material in context, focusing on Hawaii. Many of the figures are selected from a 2020 Hawaii State Energy Office report and like all material presented herein, the aim is to illuminate the landscape for educational purposes. It is by no means meant to be comprehensive. That being said, let's start with the driving motivation and take a look at **Hawaii's dependency on petroleum**:

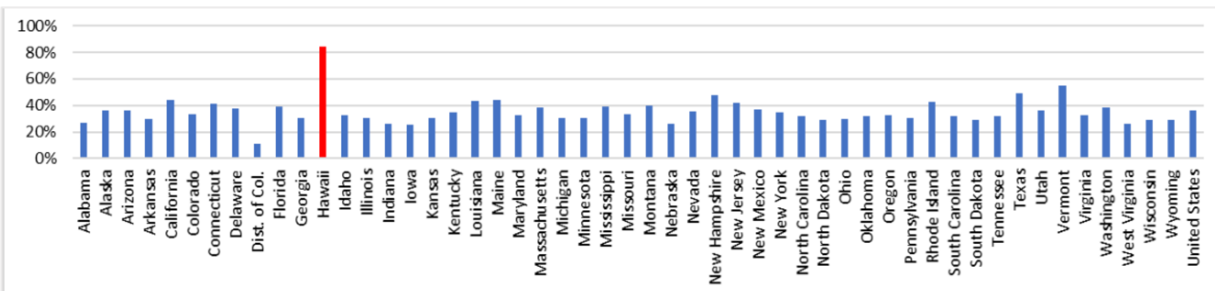
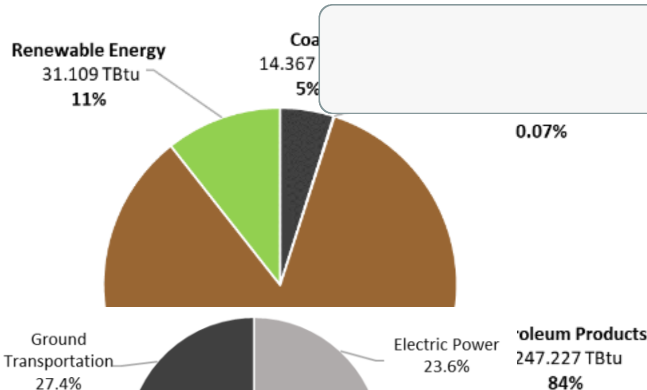


Fig. 1.1: Dependence of states on petroleum for their energy needs, 2018



> **Note**
>
> 1 BTU = 0.000293 kWh

1.1 Introduction

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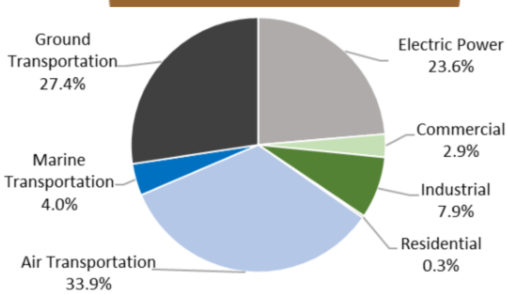

Fig. 1.3: Hawaii petroleum use by sector, 2018

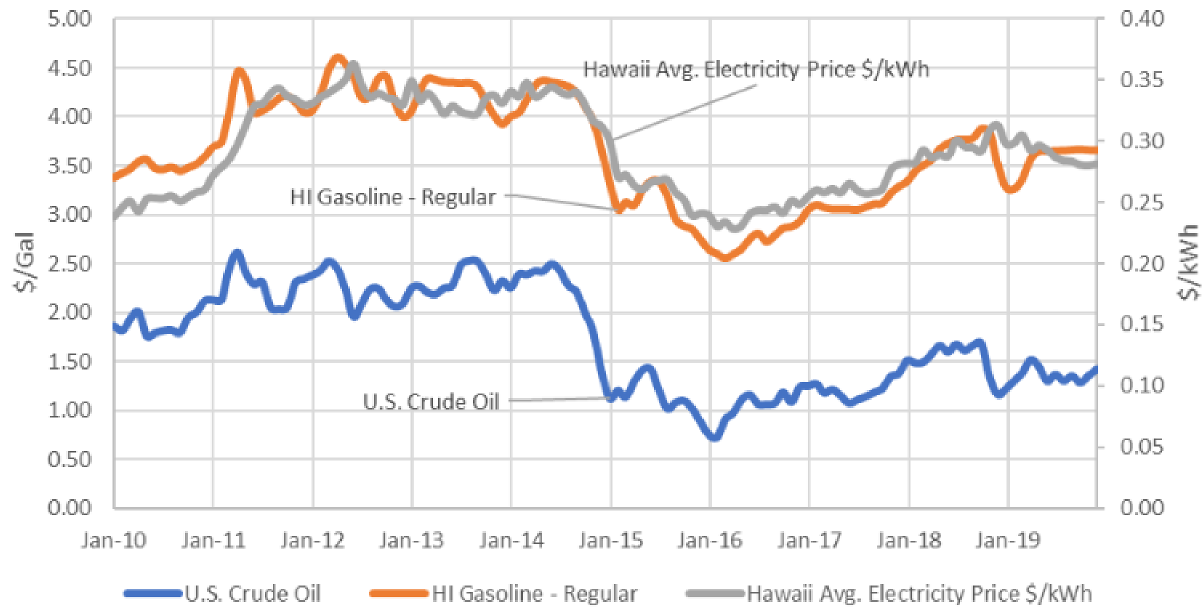

Fig. 1.4: Hawaii's dependence on petroleum.

- Ocean wave energy as a sustainable energy source
  - Where does the energy come from?
- "Benefits to society?" Phrased slightly different…"What are the problems with fossil fuels?"
  - Anthropogenic climate change
  - Finite resource
    - Who owns the resource?
    - Rate of consumption

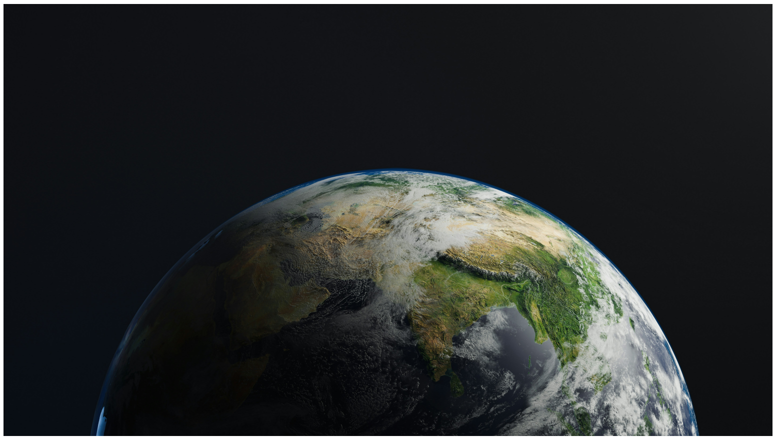

Fig. 1.5: Earth from space.

- Enhances national energy self-sufficiency and reduces reliance on imports
- Increases energy diversity
  - Why is diversity important?
  - New sectors for innovation and employment
- Land usage (debatable)

1.2 The Concept of a Successful Product Innovation

- Elements for business potential

  - Gotta start somewhere…
    - Public funding and market incentives
      - EMEC 2016: over 250 developers
      - US following lead…can see in US DOE investment profile

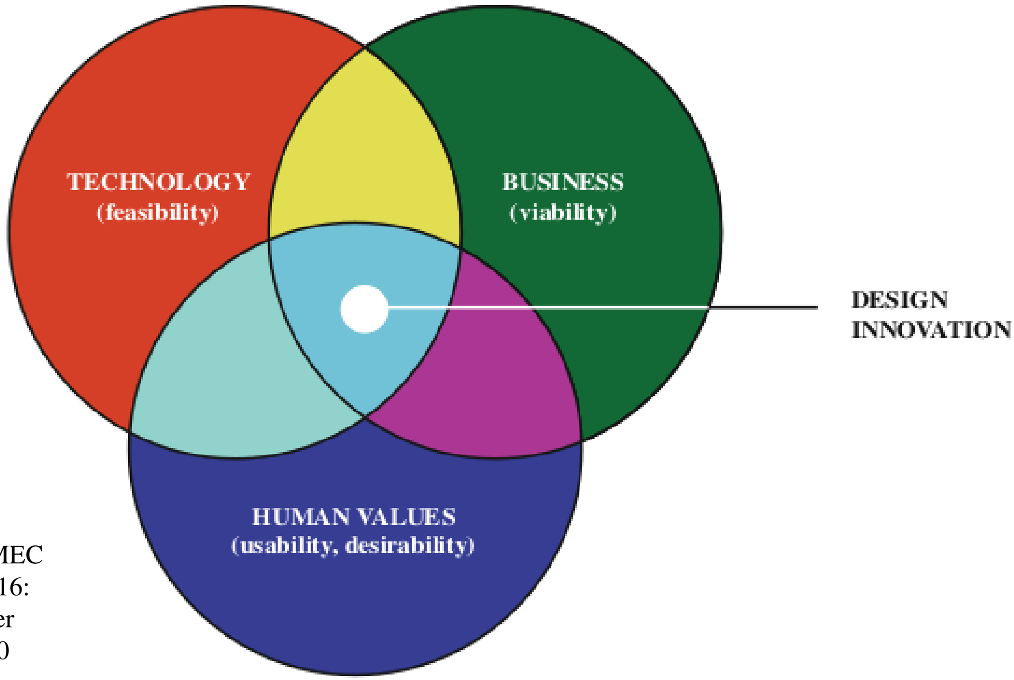

Fig. 1.7: Three key elements of successful product design innovation.

  - Business side: economic viability
    - Capital expenditure (CapEx)
      - "investments" e.g. new printer
    - Operational expenditure (OpEx)
      - "day-to-day" e.g. printer paper
    - "Levelized Cost Of Electricity" (LCOE) ($/kWh)
      - See Wikipedia page here
      - What does the energy landscape look like?
  - Where is wave energy?
    - NREL survey indicates mean $0.57/kWh in 2020

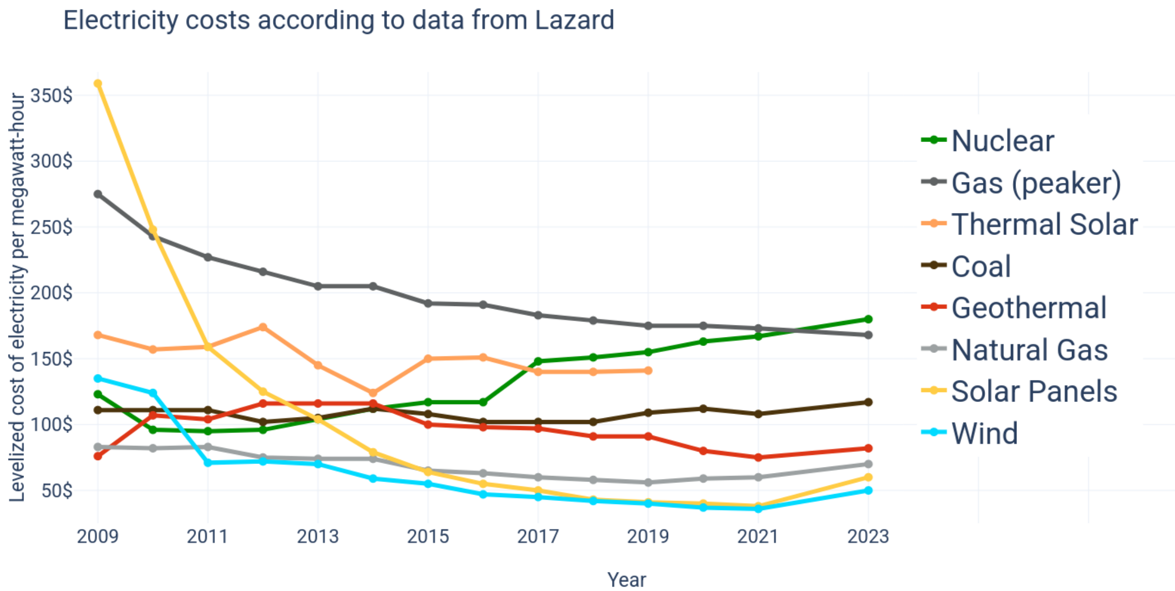

Fig. 1.8: Source: Mir-445511 via Wikimedia Commons CC BY-SA 4.0

- Very small sample
- Presumably leaders in industry who were happy to answer

– Realistically, closer to an order of magnitude difference (see 2015 OES report)

- **This is the hurdle!** (Look back at Venn diagram)
  - Technology development is active, but commercialization is still challenging
  - Need for economic viability through reduced CapEx/OpEx and proven power production
  - High costs of WEC development due to harsh offshore conditions
  - Importance of a strong track record for attracting investors

- What is the potential for wave energy in Hawaii…

Note

Much of what is discussed herein is with respect to the utility scale. However, it is important to acknowledge the scalablity of these technologies. At the smaller scale lies "Blue Economy" applications, which includes aquaculture, desalination, instrumentation, unmanned vechicles, disaster relief, micro grids, or really, powering anything not utility scale.

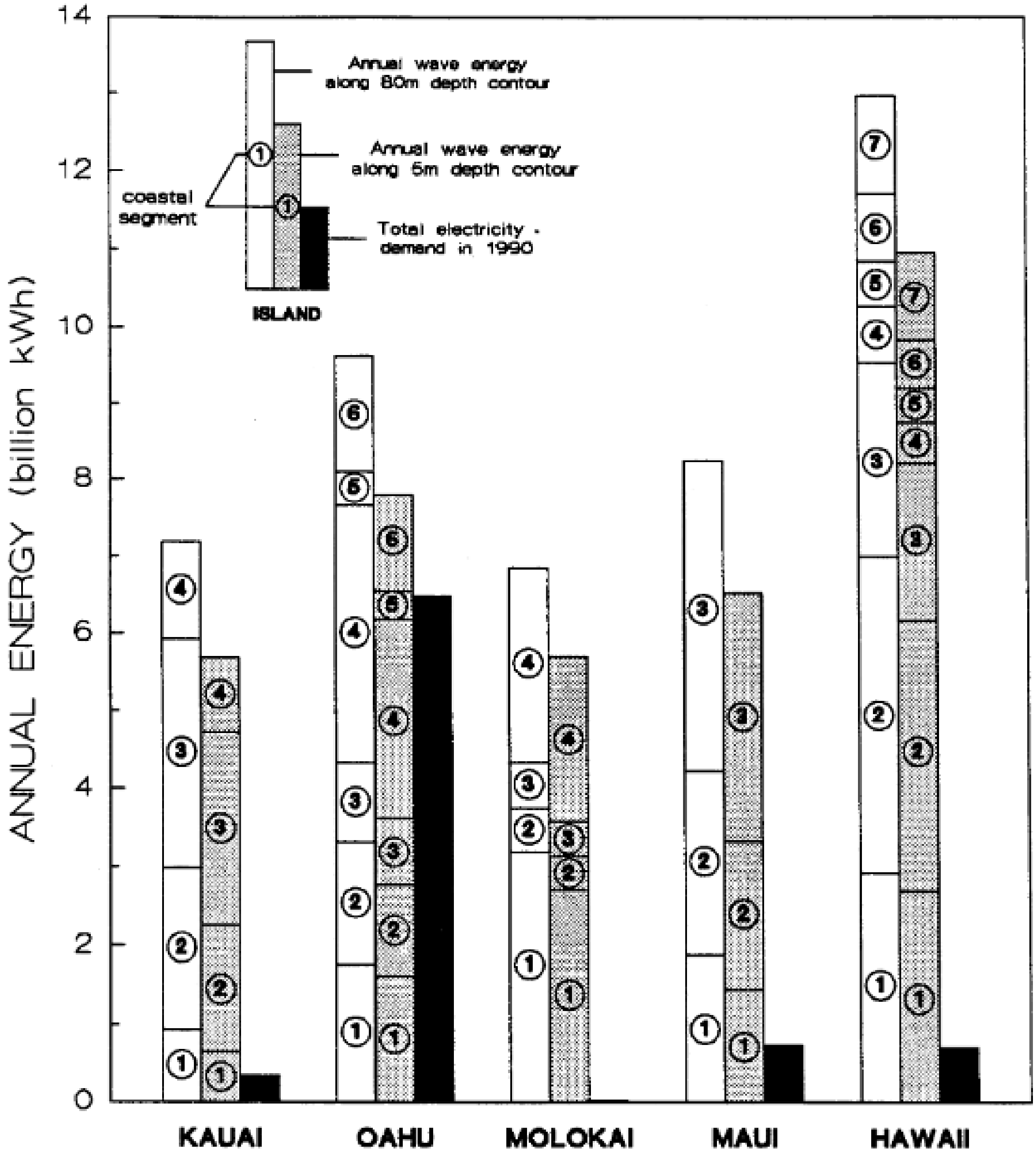

Fig. 1.9: Annual wave energy resource compared with 1990 demand. 2002 Feasibility of Developing Wave Power as a Renewable Energy Resource for Hawaii

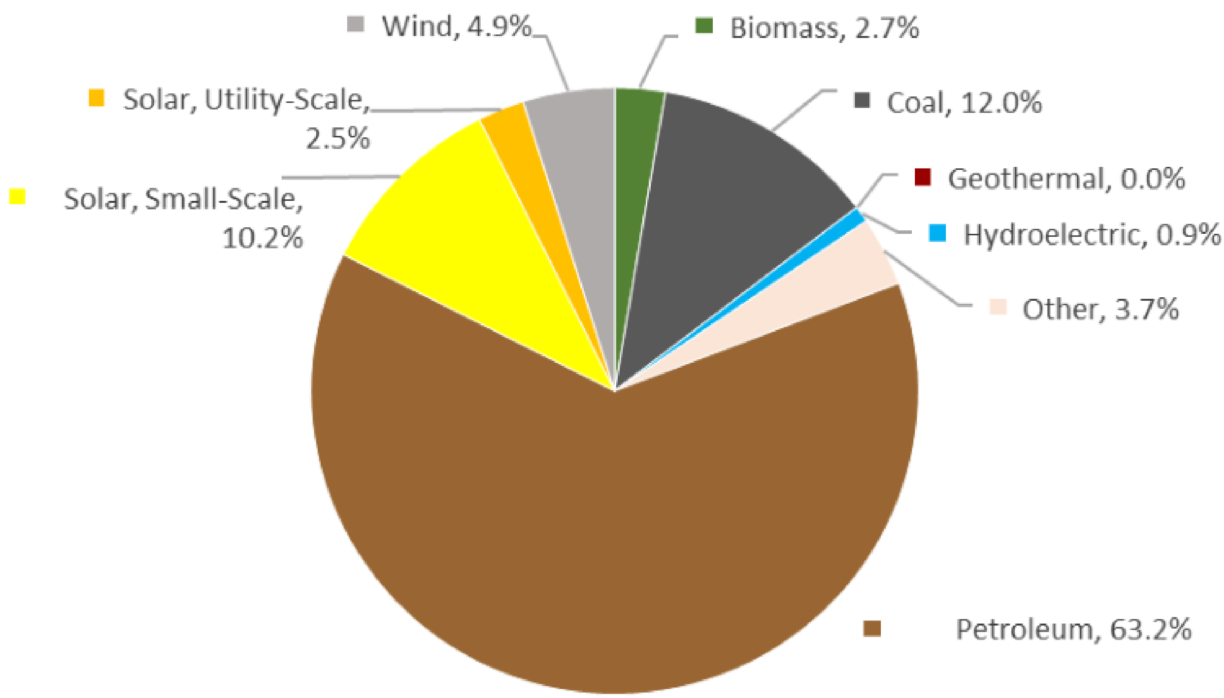

Fig. 1.10: Hawaii electricity production by source, 2019

1.3 Overview of a Wave Energy Converter (WEC)

- Emphasize the acronym…**WEC**…you'll see it a lot!!!
- Most WECs are defined by 4 subsystems
    1. Hydrodynamic capturer: absorbs wave energy.
    2. Power take-off (PTO): converts wave energy into electricity.
    3. Reaction: anchors WEC and supports other subsystems.
    4. Control and instrumentation: automates and monitors the WEC.
- Designs are VASTLY diverse
    - Why can't we all just agree on something?
    - Will see more in later chapters

1.4 Metocean Parameters Affecting WECs

- Wave regimes: deep vs shallow
    - Scale dependent (relative depth)
- Largest variability is associated with wave period
- Energy proportional to square of wave height
    - Steeper waves tend to result in better performance

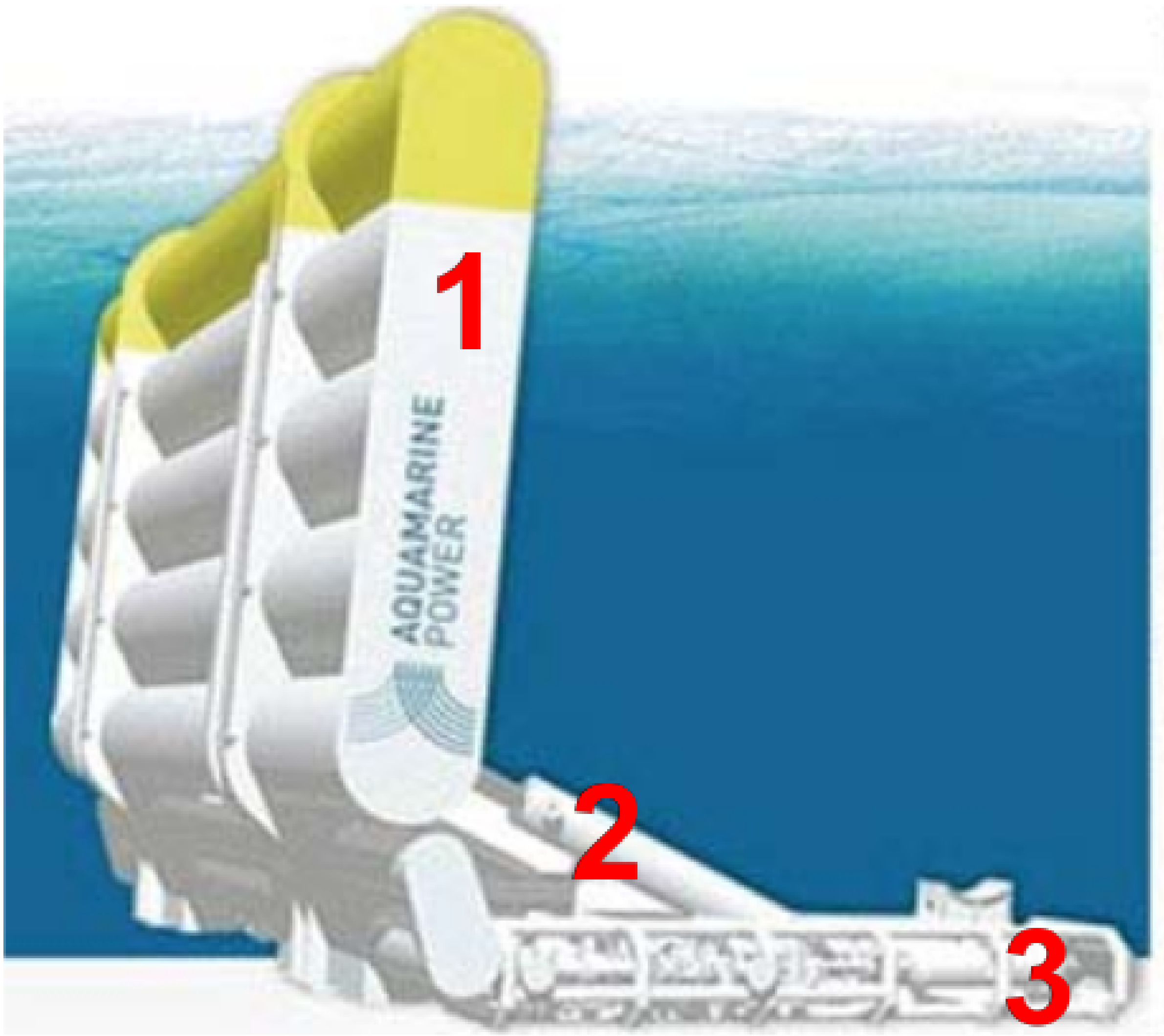

Fig. 1.11: Oyster 800 submerged flap WEC

  - However, want to stay out of breaking waves
- We established wind as primary forcing mechanism in very beginning
  - Examples of optimal regions: Southern Hemisphere, North Atlantic, West Coasts.
  - Let's look at a global animation of the wave field
- Other parameters?
  - Think "propagation"
  - Local vs global

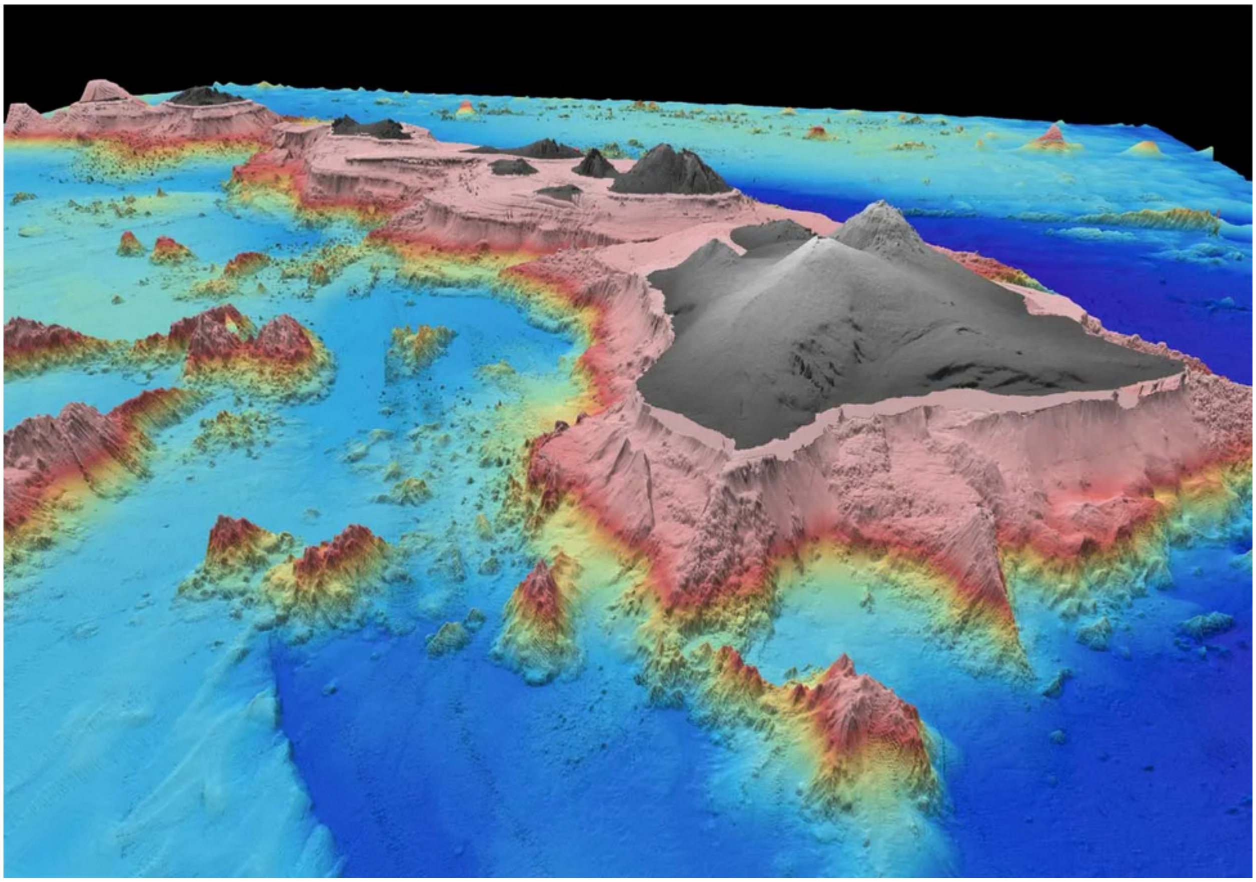

Fig. 1.12: Hawaii digital elevation model (DEM) A.K.A "bathymetry"

1.5 Essential Features of WEC

- WEC survivability in extreme ocean conditions.
  - Extreme loads
  - Fatigue cycles
  - Corrosive environment
- Low LCOE
  - Minimum maintenance.

    - Costs for ship, crew, fuel, etc. add up quick (think OpEx).
  - Smooth power and high capacity factor (see section below).
- Scalability: target is several megawatt
- Environmentally friendly

There are some technical metrics we can introduce here as well…

- Capture Width Ratio (CWR)

$$CWR = \frac{P_{absorbed}}{P_{wave} \times \text{Width}} \tag{1.1}$$

in which it is clear that a higher CWR will reduce the LCOE because the device is absorbing a higher percentage of incident energy. It should also be pointed out that $P_{absorbed}$ doesn't necessarily include the full wave-to-wire power transfer, so it's important to understand how $P_{absorbed}$ is defined.

- Theoretical limit for (hydrodynamic?) CWR…
  - (anti-) symmetric $= 50\%$ (e.g. heave point and pitching flap)
  - non-symmetric $\approx 100\%$ (e.g. Salter's Duck)
- Typical (hydrodynamic?) CWR values…
  - Floating overtopping $\approx 17\%$
  - Oscillating water column $\approx 29\%$
  - Point absorber $\approx 16\%$
  - Bottom fixed pitching flap $\approx 37\%$

Other metrics to be noted…

- Max-to-Mean Ratio
  - Influences engineering design
  - Can be reduced with multiple PTOs
    - Can you explain why?
  - Lower means smoother power and more uniform design
- Weight-to-Power Ratio
  - Gives indication of amount of material relative to power rating

Warning

Care should be taken when comparing metrics, as they often ignore nuance.

A good wave absorber must be a good wave-maker

1.6 WEC Economics

- Annual Energy Production (AEP)
  - Total energy produced over a one year period

$$
\begin{aligned}
AEP &= \text{Annual Average Power Production} \times 8760\text{hrs/yr} \\
AEP &= P_{wave} \times \text{Width} \times \epsilon \times \%_{duty} \times 8760\text{hrs/yr}
\end{aligned}
\tag{1.2}
$$

in which P_{wave} is the incident wave power per unit width, ϵ is the wave-to-wire efficiency of the device, and $\%_{duty}$ is the annual duty cycle expressed as a percentage.

Note

Most of these variables are dependent on the wave conditions. Therefore, the AEP is often determined through element-wise matrix multiplication then integrated.

- Capacity Factor
  - The National Renewable Energy Laboratory (NREL) defines this as "the ratio of the actual time-averaged power generation to the maximum possible power generation of a particular power plant."

$$
\text{Capacity Factor} = \frac{\text{Annual Average Power Production}}{\text{Rated Power Capacity}} \tag{1.3}
$$

in which the "Annual Average Power Production" can be estimated from (1.2) above and the "Rated Power Capacity" (for most intents and purposes, same as "installed power capacity") is "the maximum power than can be generated over a sustained time frame, say one or more hours, without damaging or overheating the equipment" (see Chap. 5).

Note

The "Rated Power Capacity" is often determined by the generator performance specifications.

- Economically speaking: many small WECs $\neq$ one large WEC
  - There are many benefits to a larger system
    - What constitutes a "large system"?
- AEP is more meaningful than "Rated/Installed Power Capacity"…don't let the media fool you!!!
- Proximity is another factor to consider

1.7 Power Take-Off Systems

- Slow oscillations with high forces to fast rotation (electric generator).
- PTO efficiency is crucial for overall system performance.
- Most efficient when restricted to one degree of freedom (DOF).
  - Generally less complex and easier to optimize.
- Different PTO systems (hydraulic, mechanical, direct drive).
  - Need to temporarily store/smooth energy.
  - Handle short term power overload.

  - Handle system faults and control losses.
- Advanced control strategies can enhance power production but increase system wear.

1.8 Summary, Future Outlook, and Conclusions

- Wave energy has a strong potential as part of the future renewable energy mix.
- Ongoing technological improvements needed to reduce costs and increase reliability.
- Opportunities for innovation in scaling, durability, and maintenance.
- Ocean wave energy has significant long-term potential.
- Success depends on innovation, economic viability, and optimal deployment.
- WEC technology continues to evolve, with many challenges ahead.

CHAPTER TWO

CHAPTER 2: THE WAVE ENERGY SECTOR

- Sparse at best in Hawaii, but high potential to adapt
  - Ship yards
  - Marine construction
  - Environmental permitting and planning
  - Universities
- Demand is there: Hawai‘i CLEAN ENERGY INITIATIVE
  - "In 2023, Governor Josh Green, M.D. renewed Hawai‘i's commitment to achieve the nation's first-ever 100 percent renewable portfolio standards (RPS) by the year 2045."

2.1 Introduction

- Why wave energy and why now?
  - environmental impact: climate change
  - fossil fuel depletion
    - what does this mean for the price of oil?
  - energy security
  - energy diversity
  - LOCAL job creation
    - Saw the potential…inter-island export?
- What are the local social issues?
- What does a solution look like for Hawaii?
  - CSI-WECs
  - Co-design
- Most of money is spent on materials and workmanship as opposed to handling the fuel
- Recall the challenge…techno-economic feasibility leaves wave energy still in R&D phase
  - Focus on optimization of structures, operations, controls, etc.
  - Still heavily dependent on political support.
- LCOE margin is less for island communities…

- Hawaii has two options: 1) wait and buy or 2) build

2.2 Global and Regional Estimates of Wave Energy Potential

- What waves are we talking about?
  - "sea states"
  - wave climate
- Wave energy as a vast resource…
  - about 3.5 TW global resource (theoretical)
    - extrapolating studies suggests 2/3 can be recovered
  - global average electrical power consumption in 2008: about 2 TW
  - key takeaway: wave energy alone has potential to meet global demand
    - realistically, it has the potential to diversify the portfolio (recap importance)

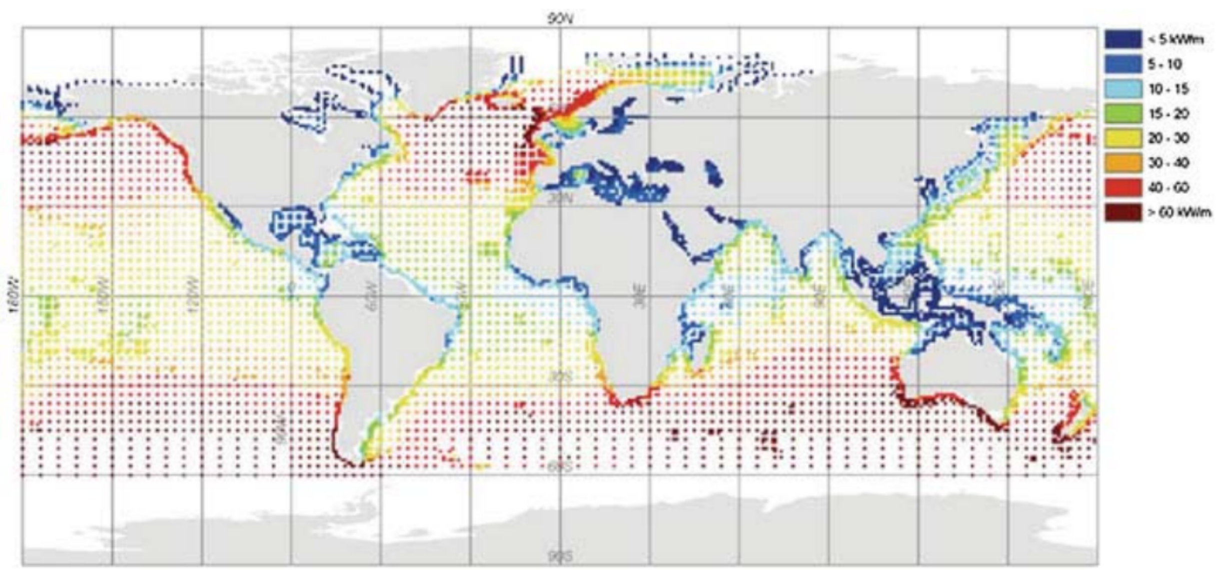

Fig. 2.1: Annual gross wave power (theoretical)

- We can see the hot spots in the figure above
  - Northern and Southern oceans
  - West coasts (land perspective)
    - animation from Chapter 1 should have given clue why
- Recent 32-year hindcast for Hawaii Medina et. al., 2019 PNNL-29370
  - Recall metric: max-to-mean
  - Take look at spatial distributions…
- Observations
  - Annual averages appear to be on par with previous studies

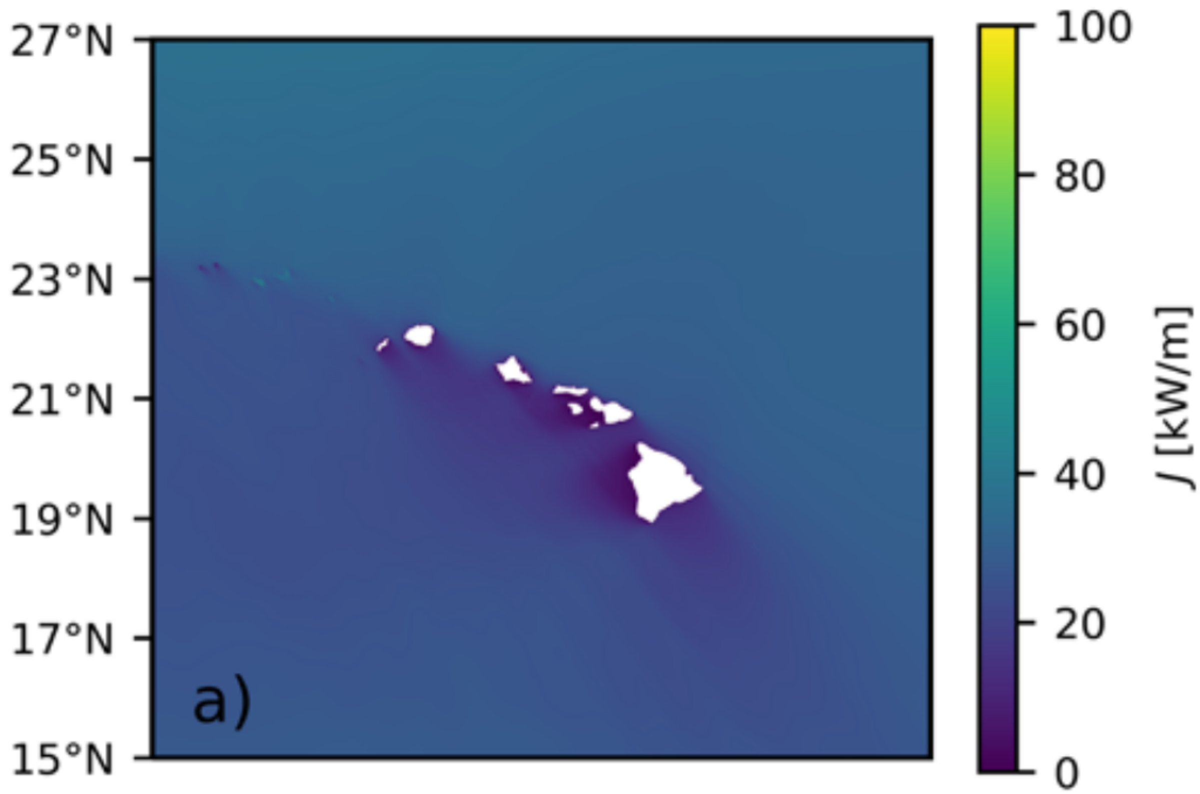

Fig. 2.2: Annual

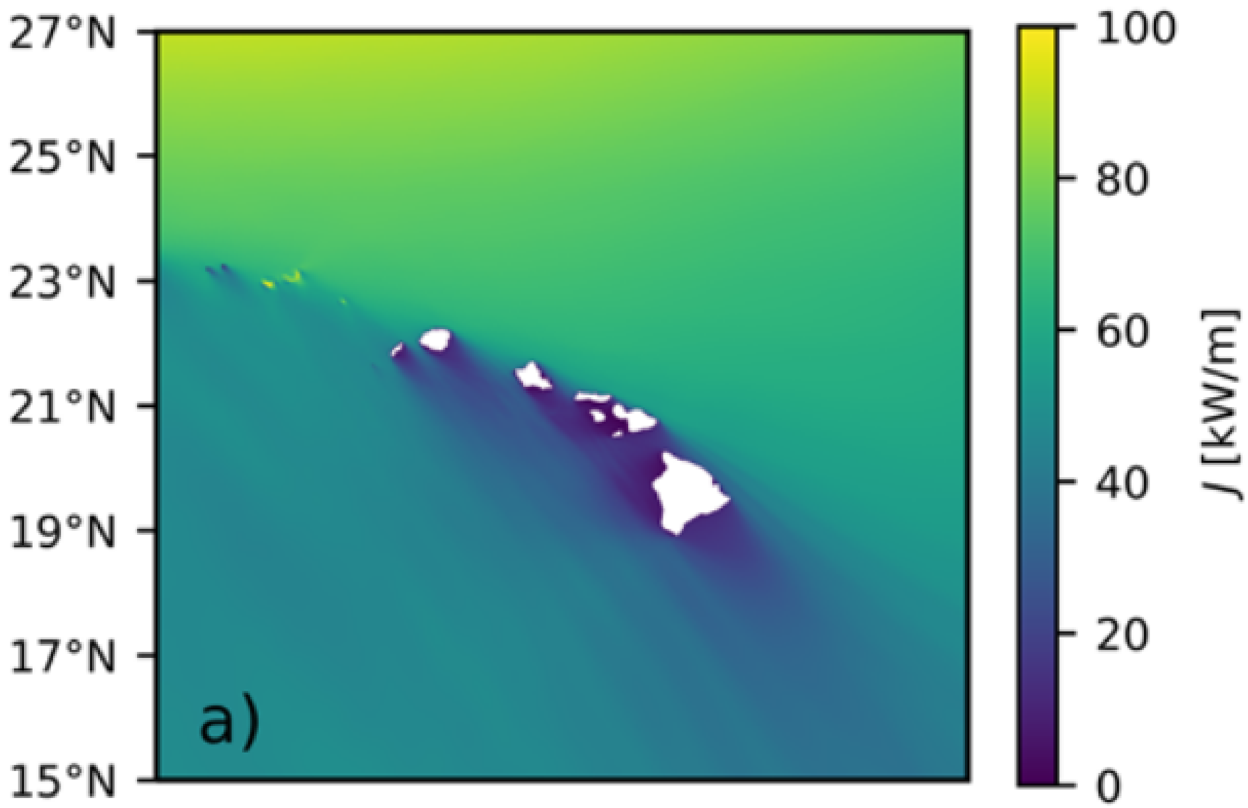

Fig. 2.3: January

- Northern coasts experience greatest power
    - Look at example…

$$\text{Deep Water Wave Power} = \frac{\rho g^2}{64\pi} H^2 T$$

For the sake of argument, assume a wave height of 10ft with a period of 15s in deep water. Plugging in the values gives a wave power of about 735kW/m (nearly 1MW/m), which is off the chart in the figure above.

Fig. 2.4: Wave power in perspective.

Obviously this is a big wave, but it's not unheard of on the North Shore. On Jan 6th 2024, the Waimea buoy recorded a **significant** wave height of about 10ft with a **peak** period of 15s, which are statistical properties of a wave field. Of course this doesn't happen often, hence the averages are lower. I should also point out that the photo is a breaking wave, which is larger than the offshore height due to shoaling, but it helps to put things into perspective when we talk about wave power **per metere**.

Note

Wave energy (and power) scales with the square of the wave height!

2.3 Historical Development of Wave Energy Converters (WECs)

- Early attempts to harness wave energy date back to the 1800s.
- The modern era of wave energy research began in the 1970s, influenced by the oil crisis.
    - Stephen Salter: "Salter's Duck"…
- Current focus on commercial-scale WEC development
    - Strongest efforts in Europe
    - USA has been picking up pace

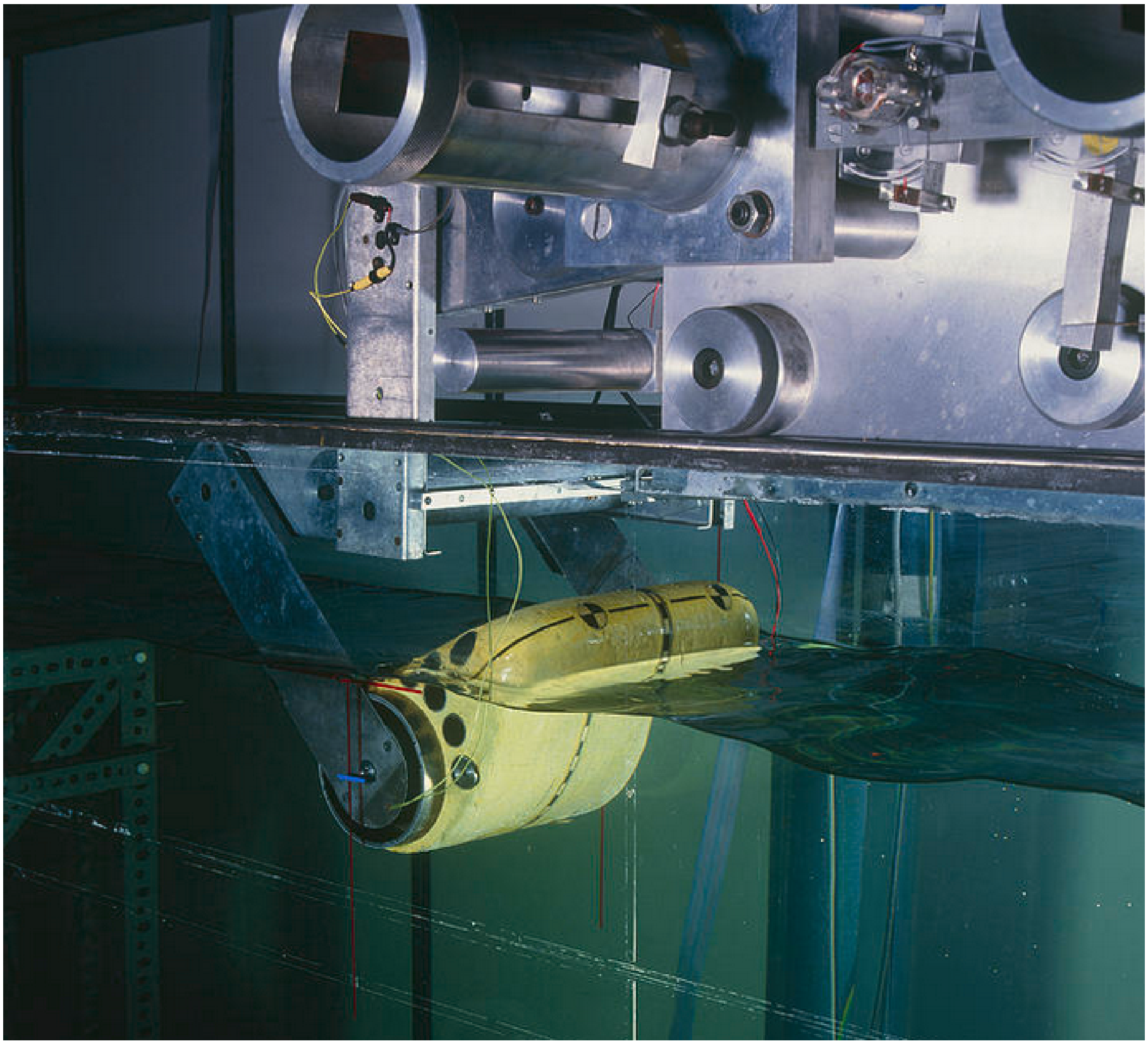

Fig. 2.5: Testing of asymetric body (yellow device) in wave flume.

2.4 Types of Wave Energy Converters

- Different ways to categorize, but in general categories are quite limited
- For eample, three main types of WECs:
  1. Terminators: devices with large horizontal extensions parallel to wave propagation.
  2. Attenuators: devices perpendicular to wave propagation
  3. Point Absorbers: devices with small extensions compared to the wavelength.

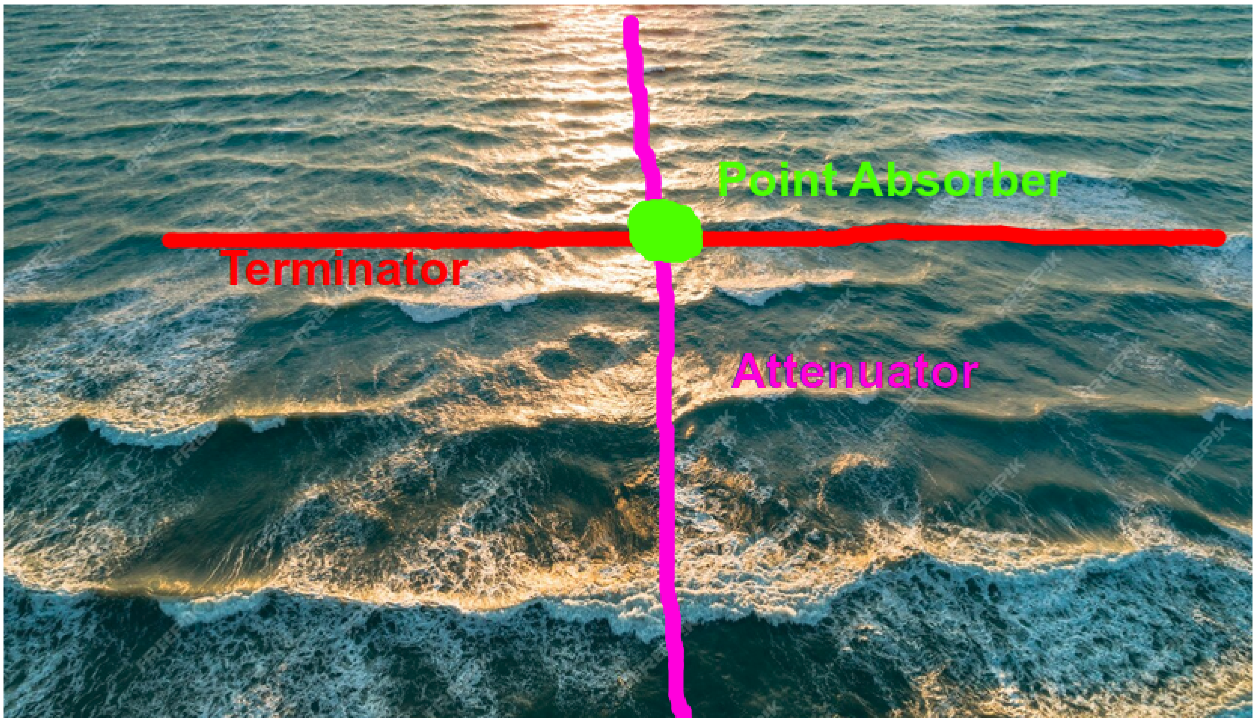

Fig. 2.6: Categorization of WECs

- Within these three categories, what are the main features?
- Other categorizations include
  - location
    - Onshore WECs: fixed to the coast (e.g., oscillating water columns).
    - Near-shore WECs: installed in shallow waters, often bottom-mounted.
    - Offshore WECs: floating devices in deep waters, where waves are not influenced by the seabed.
  - working principles, for example…

Note

This is a **VERY** small subset of examples and there is no silver bullet in design. Alot is dependent upon location, resources, etc.

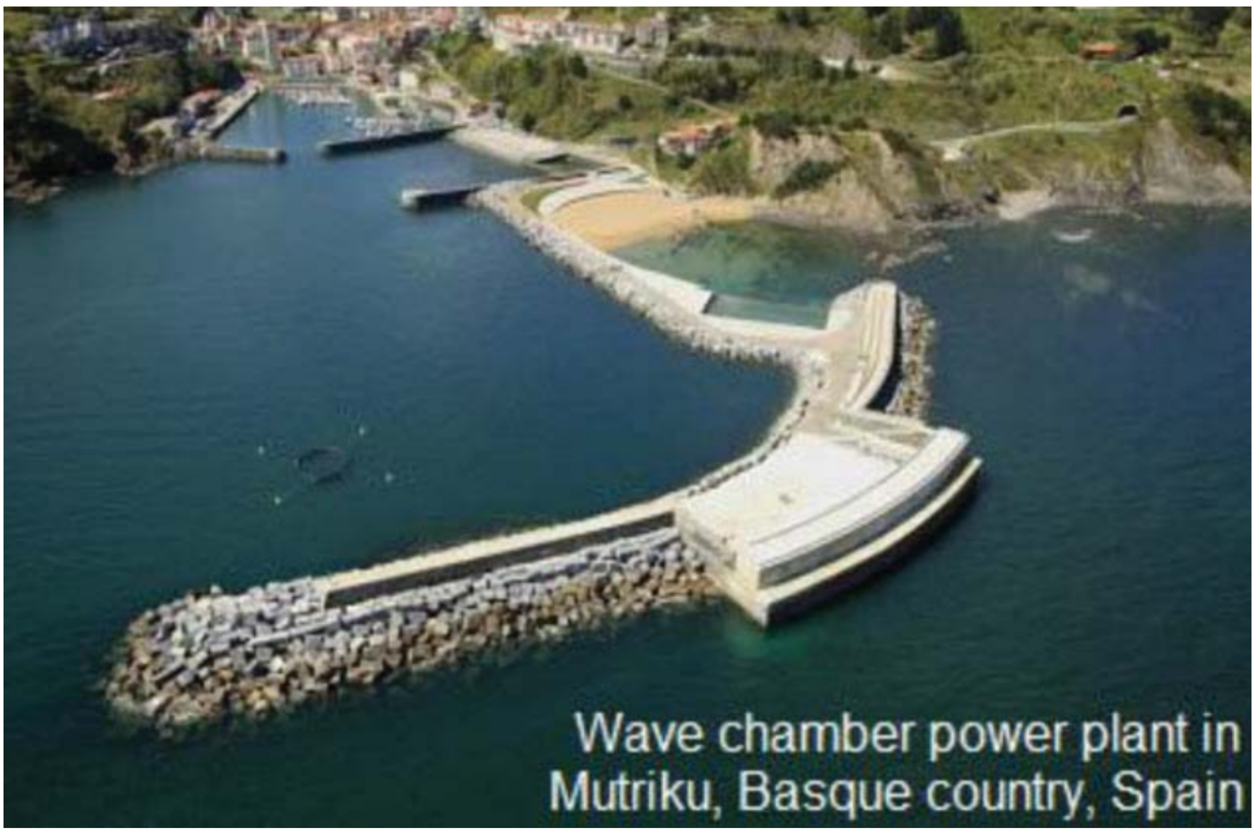

Fig. 2.7: Oscillating Water Column (OWC)

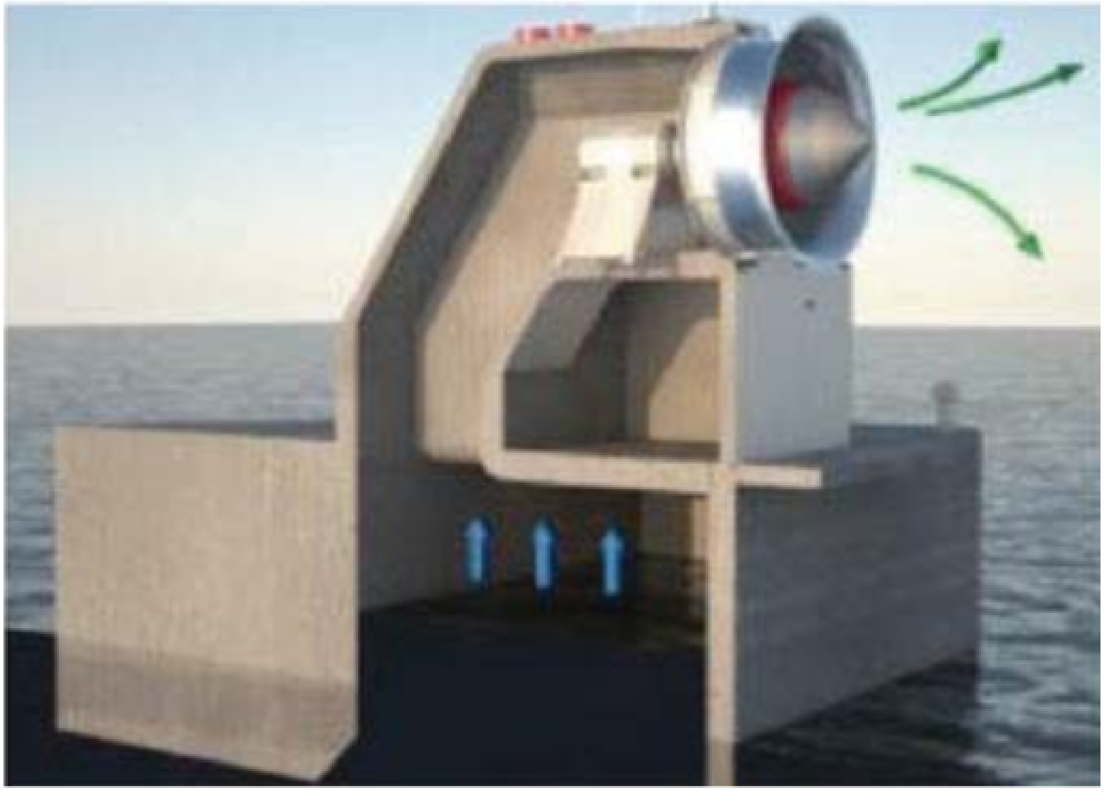

Fig. 2.8: OWC principles

Fig. 2.9: Pelamis attenuator

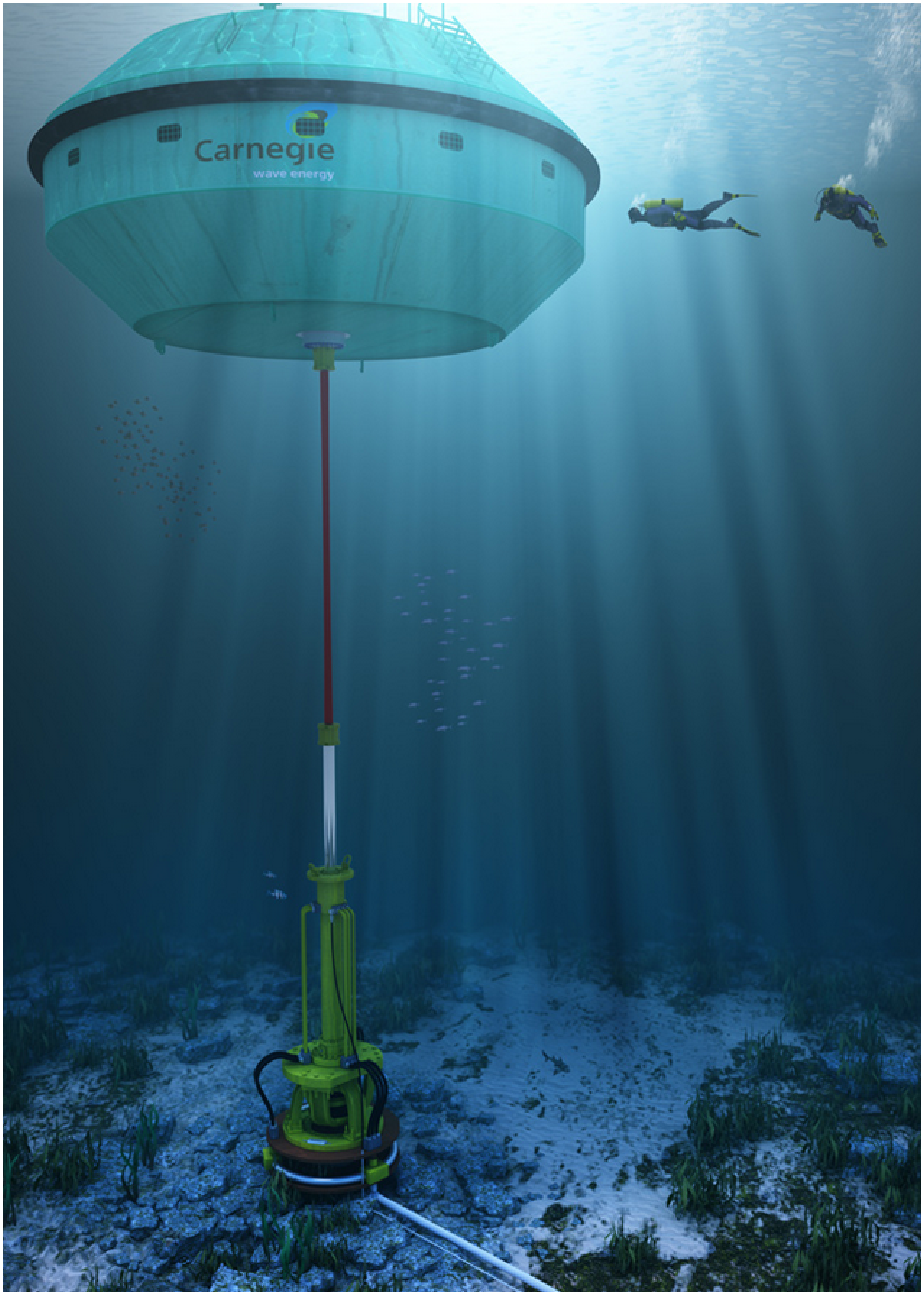

Fig. 2.10: Carnegie CETO buoy

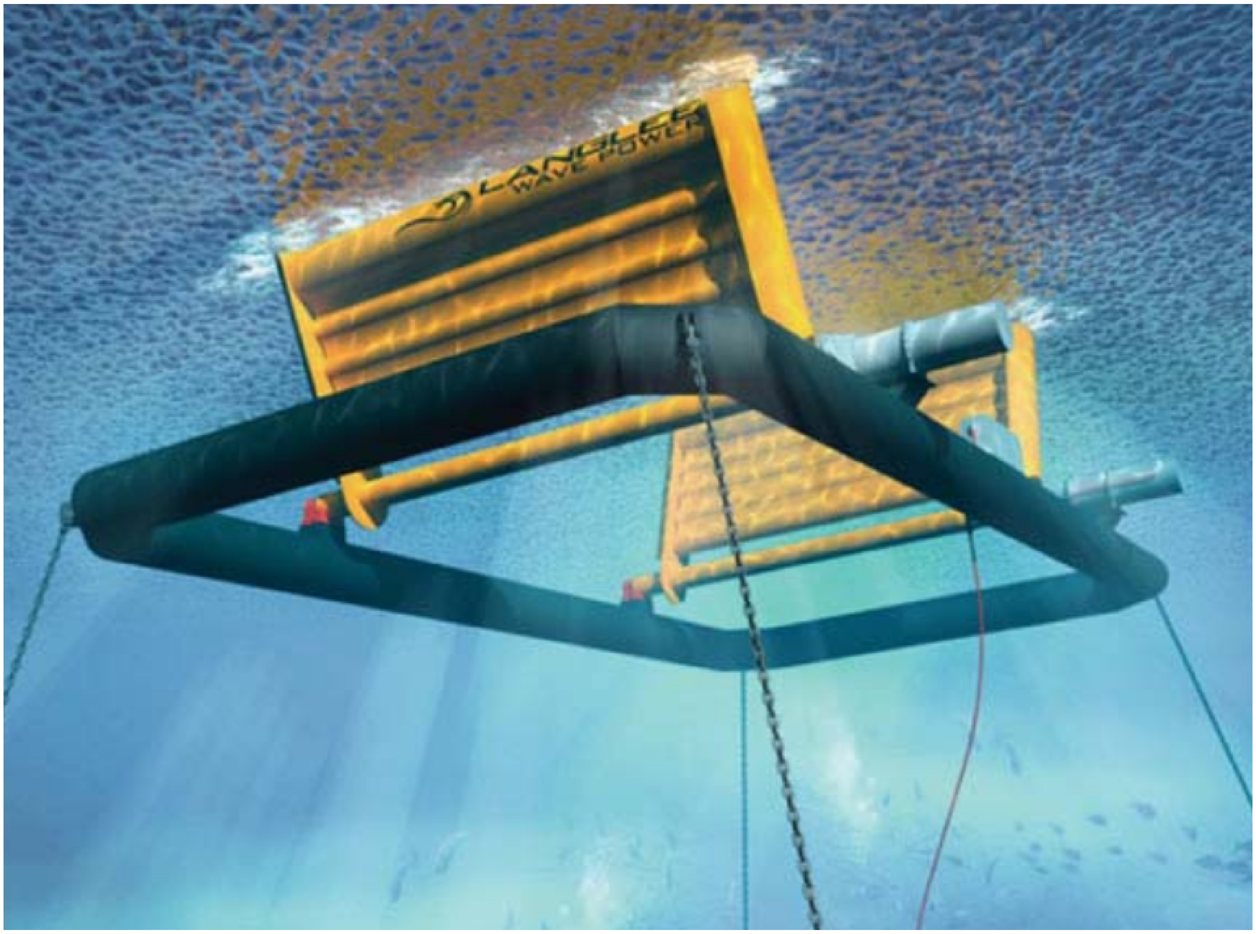

Fig. 2.11: Langlee dual pitching flap

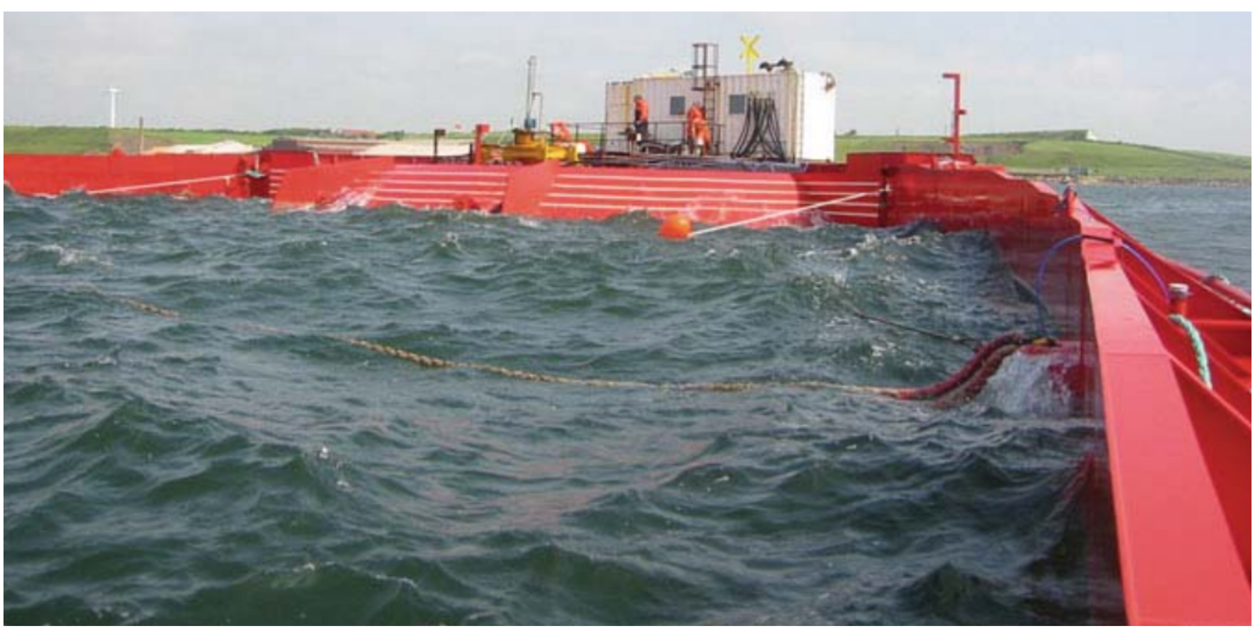

Fig. 2.12: Wave Dragon overtopping

Fig. 2.13: Wavestar multibody

2.5 Testing and Development of WEC Prototypes

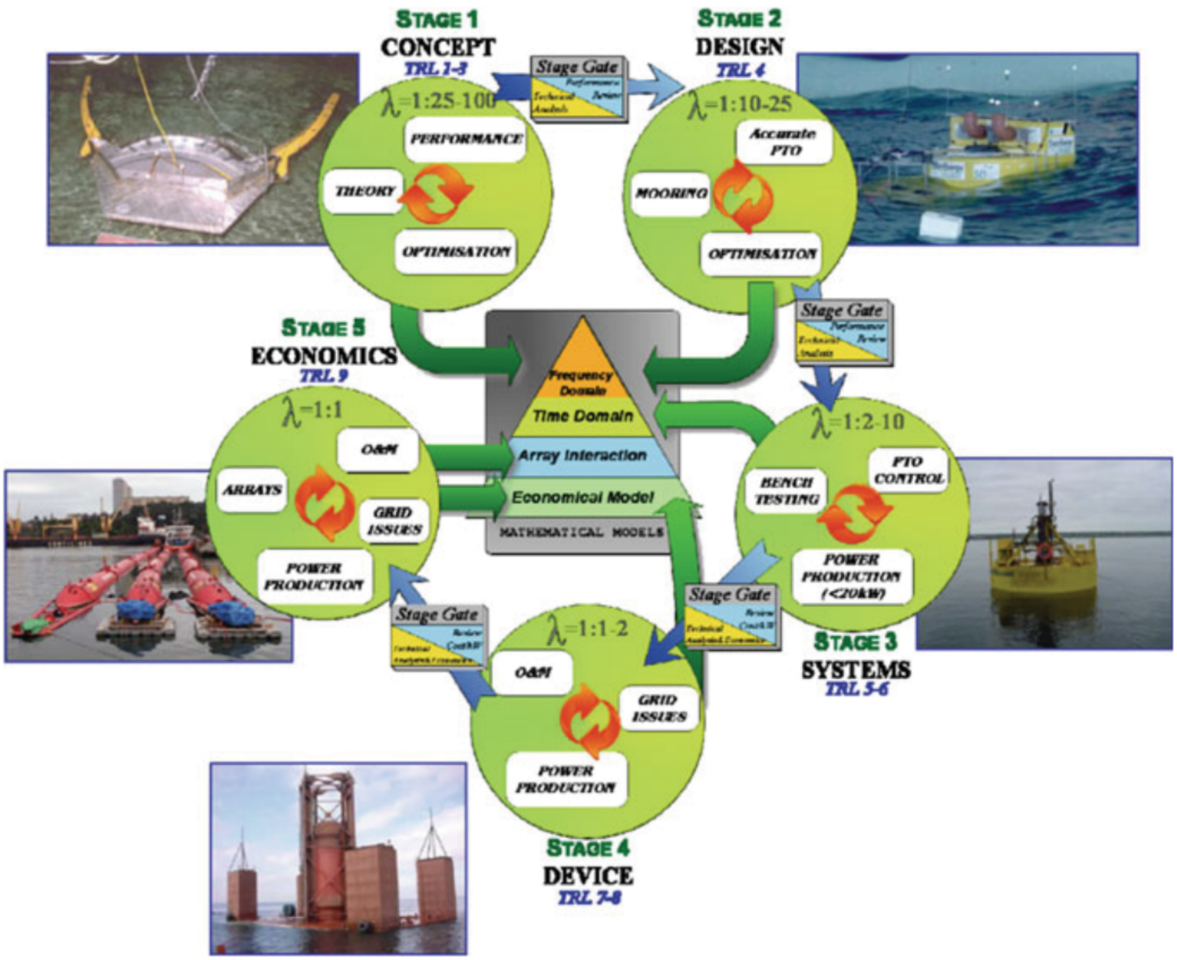

Fig. 2.14: Conceptual develpment flow diagram

- Technology Readiness Level (TRL): metric used in development process
  - TRL 1-3: “stage 1: concept”
  - TRL 4: “stage 2: design”
  - TRL 5-6: “stage 3: systems”
  - TRL 7-8: “stage 4: device”
  - TRL 9: “stage 5: economics”
- In USA, we’re largely in stages 3-4 range, with a few devices exploring commercial activity
  - Here in Hawaii, we’re still largely in stages 1-2, with a few efforts pushing into stage 3
- Real-sea testing is crucial for proving the feasibility and durability of WECs
  - Devices are built/tuned to site characteristics
  - Europe is littered with test sites
- USA, hardly any test sites, BUT…

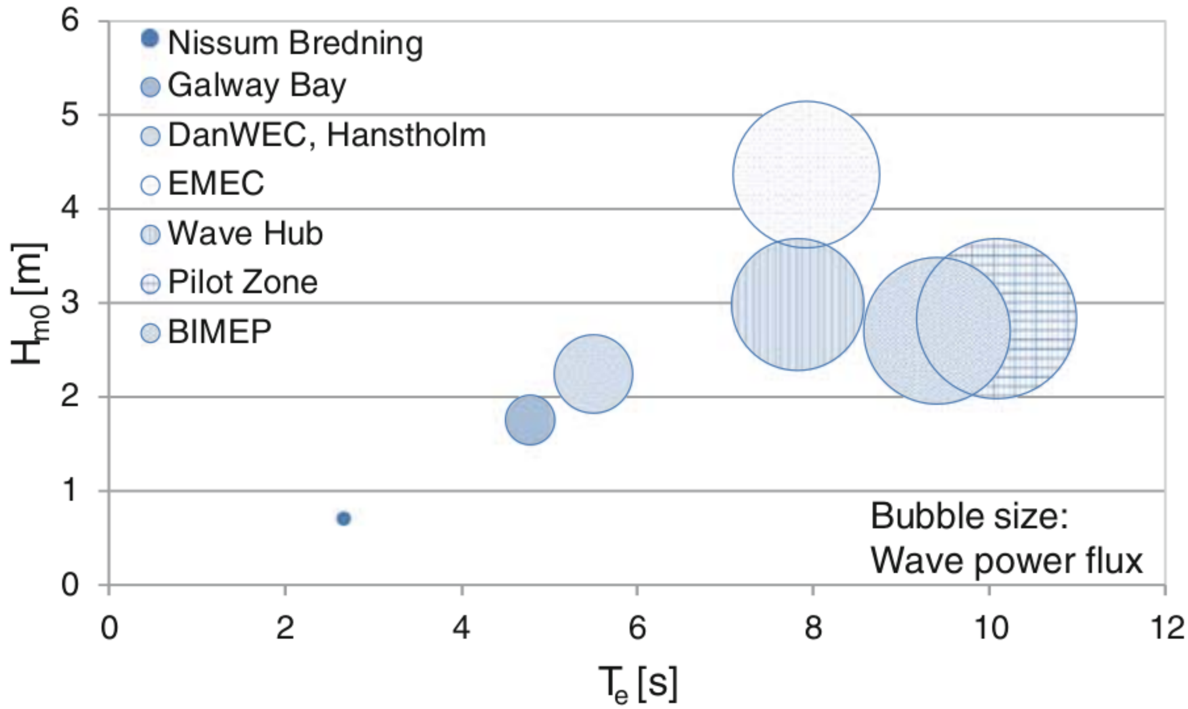

Fig. 2.15: Distribution of wave energy test sites in Europe

- Hawaii hosts one of the few: WETS, with more hopefully to come online soon

The video highlight clip below showcases some of the WEC deployments at WETS, with emphasis on the Azura device. The site is still actively maintained by HNEI's Ocean Energy group under the supervision of the US Navy, with devices being tested from around the world.

2.6 Summary, Future Outlook, and Conclusions

- Wave energy holds significant promise as part of the global renewable energy portfolio.
- International collaboration and policy support as key to advancing the wave energy sector.
- Challenges remain in terms of cost reduction and technical feasibility.
- Continued development of WECs through research, optimization, and scaling.
- With continued R&D, wave energy can play a critical role in a diversified, sustainable energy future.
- Hawaii Marine Energy Center (HMEC)

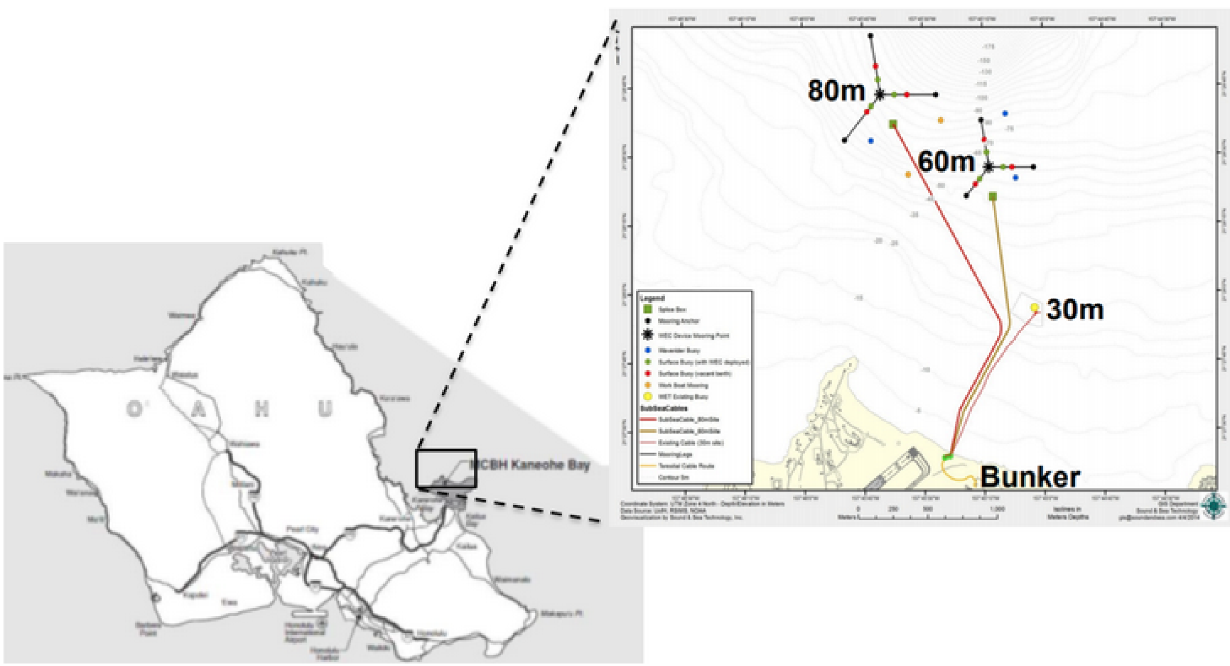

Fig. 2.16: Hawaii Wave Energy Test Site (WETS)

CHAPTER

THREE

CHAPTER 8: POWER TAKE-OFF SYSTEMS FOR WECS

Let's start with some (informal) definitions…

- Power Take-Off…**PTO**…you'll see it a lot
  - convert absorbed wave energy
  - when referring to the PTO, it's important to understand the end product (e.g. mechanical or electrical)
- Energy - capacity to do work (fundamental)…comes in many forms (kinetic, potential, etc.)
- Work - amount of energy transferred when a force acts on an object over a distance
- Power - rate at which energy is transferred. In other words the rate at which the work is done

A simple mechanical model for a WEC…

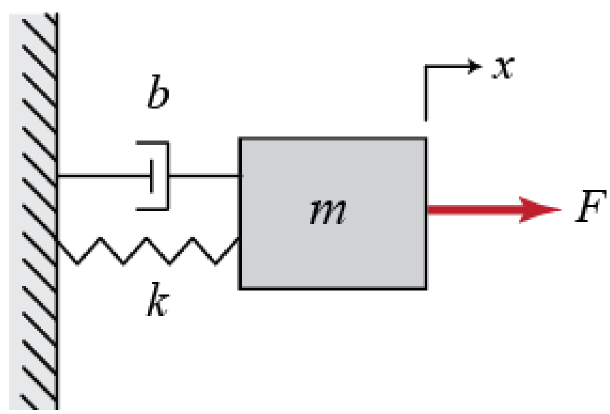

Fig. 3.1: Damped oscillator

From an engineering perspective, the study of WEC systems largely involves the study of vibrations and control theory with depth in hydrodynamics and mechanics. This is why the research is largely carried out by ocean and mechanical engineers. That being said, there are many facets to WEC systems, in which engineering is only one of them.

- General force concepts you need to know…
  1. inertia
  2. damping
  3. restoring
  4. excitation
- Of these, damping is of the form which gives absorption
  - What happens if there is no damping?

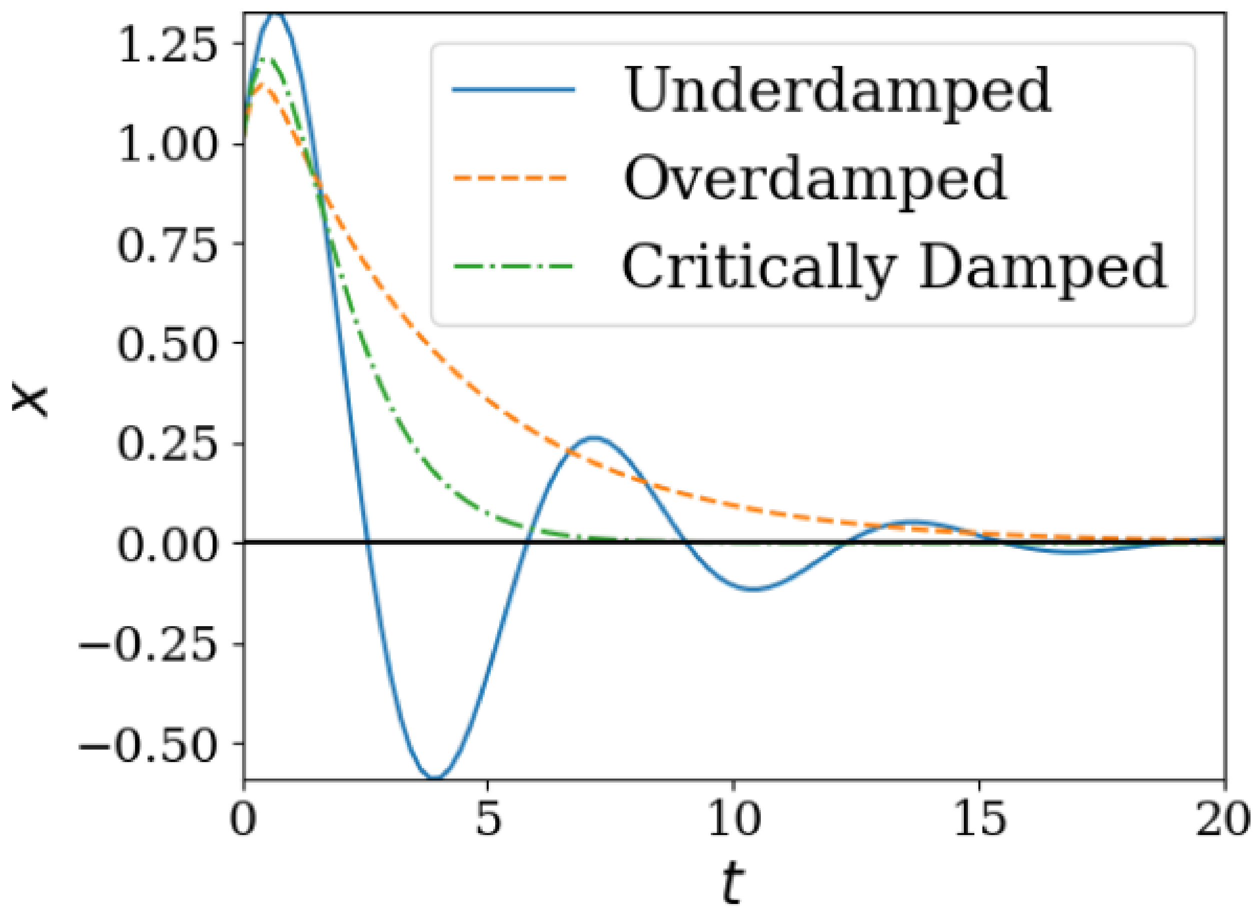

Fig. 3.2: Different forms of damping

3.1 Introduction

Start with the big picture…how do we get from A to B?

- "wave-to-wire" -> there is a constant flow/transfer of energy
  - waves power is captured/manipulated by device geometry
    - e.g. wave force acting on a body causes it to move
  - mechanical-mechanical conversion
    - e.g. linear body motion converted to shaft rotation
  - mechanical-electrical conversion
    - e.g. rotary generator
- PTO systems impact the efficiency, cost, and structural dynamics of WECs.
  - Directly affects the LCOE
  - Represent 20-30% of the CapEx
  - Reliability and maintenance (OpEx)

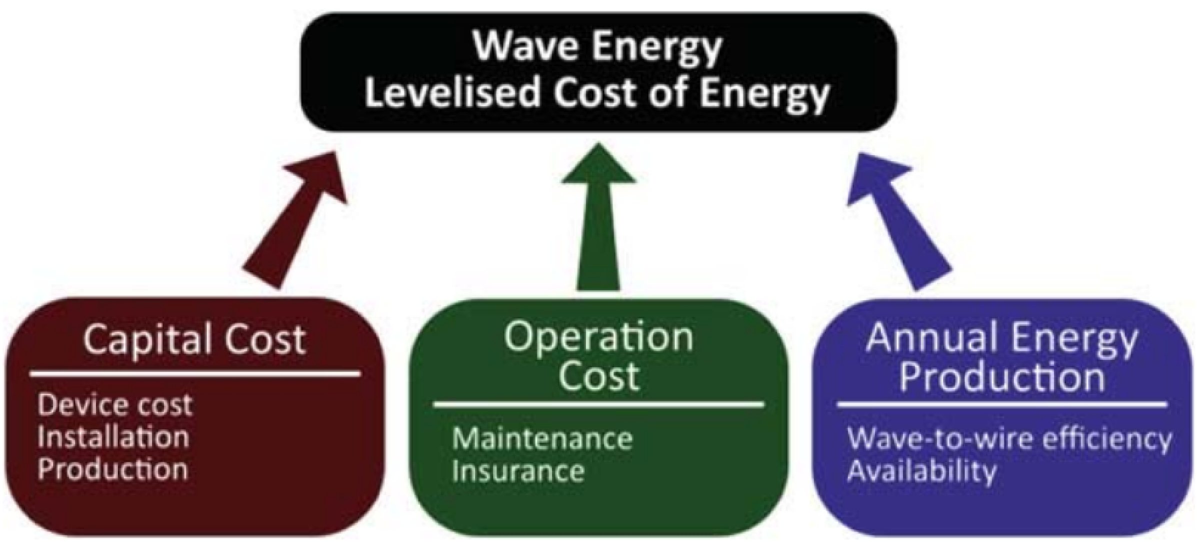

Fig. 3.3: Different forms of damping

- Designing efficient PTO systems is a major challenge **due to variability in wave energy and harsh marine environments**.
  - True for any ocean system…look at wave spectrum
  - Unconventional goal…resonance is a good thing
  - Impedance
- PTO is where most research is focused today
  - Efficiency vs Cost

3.2 Types of PTO Systems Overview

- PTOs just as diverse as WEC bodies
- Main categories include
  - air turbines
  - hydraulic systems
  - hydro turbines
  - direct mechanical drives
  - direct electrical drives

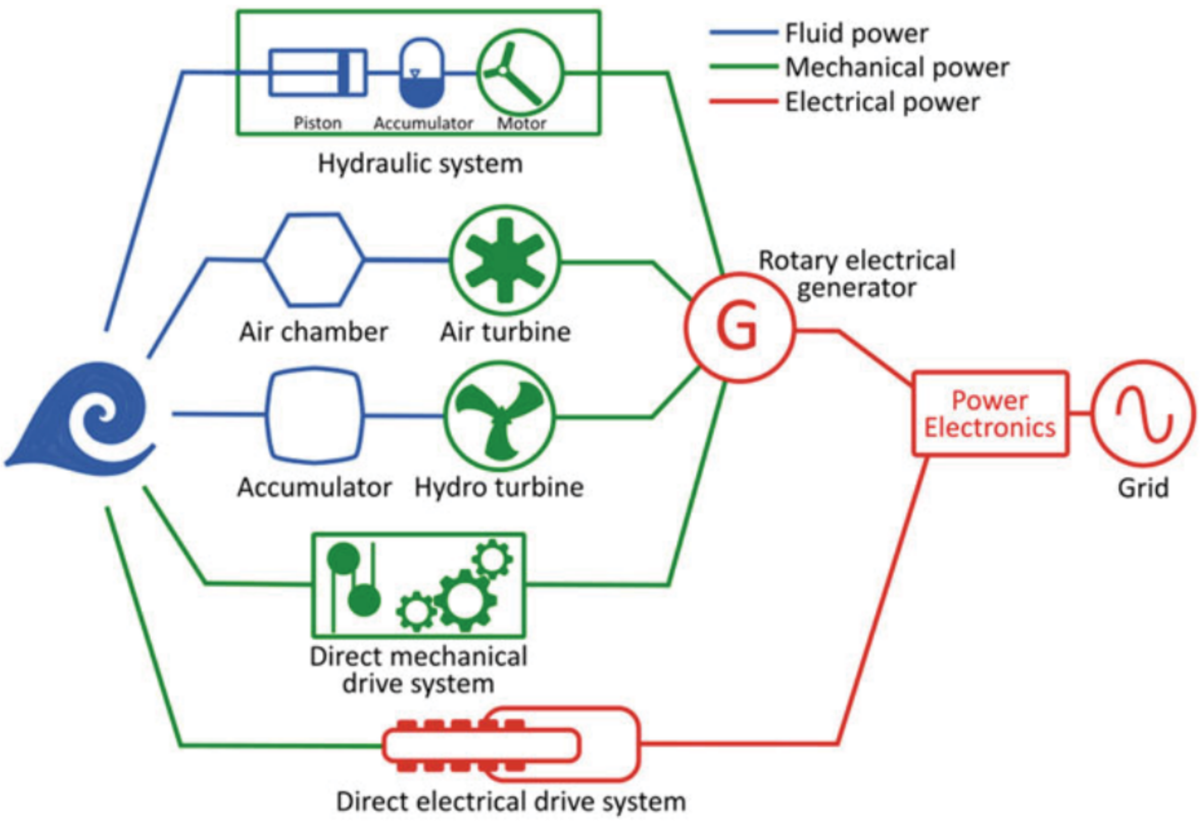

Fig. 3.4: Different types of PTO systems

- Others not mentioned include advanced materials and/or properties
  - Electroactive polymers
  - Triboelectric
  - Piezoelectric

3.3 Air Turbines

- Air turbines are used primarily in Oscillating Water Column (OWC) devices.
  - Examples of self-rectifying air turbines include Wells, Impulse, and Denniss-Auld turbines.
    - Wells turbines are simple but not self-starting
    - Impulse turbines are more efficient but require more maintenance
  - Reaction type - lift
  - Floating and fixed bottom

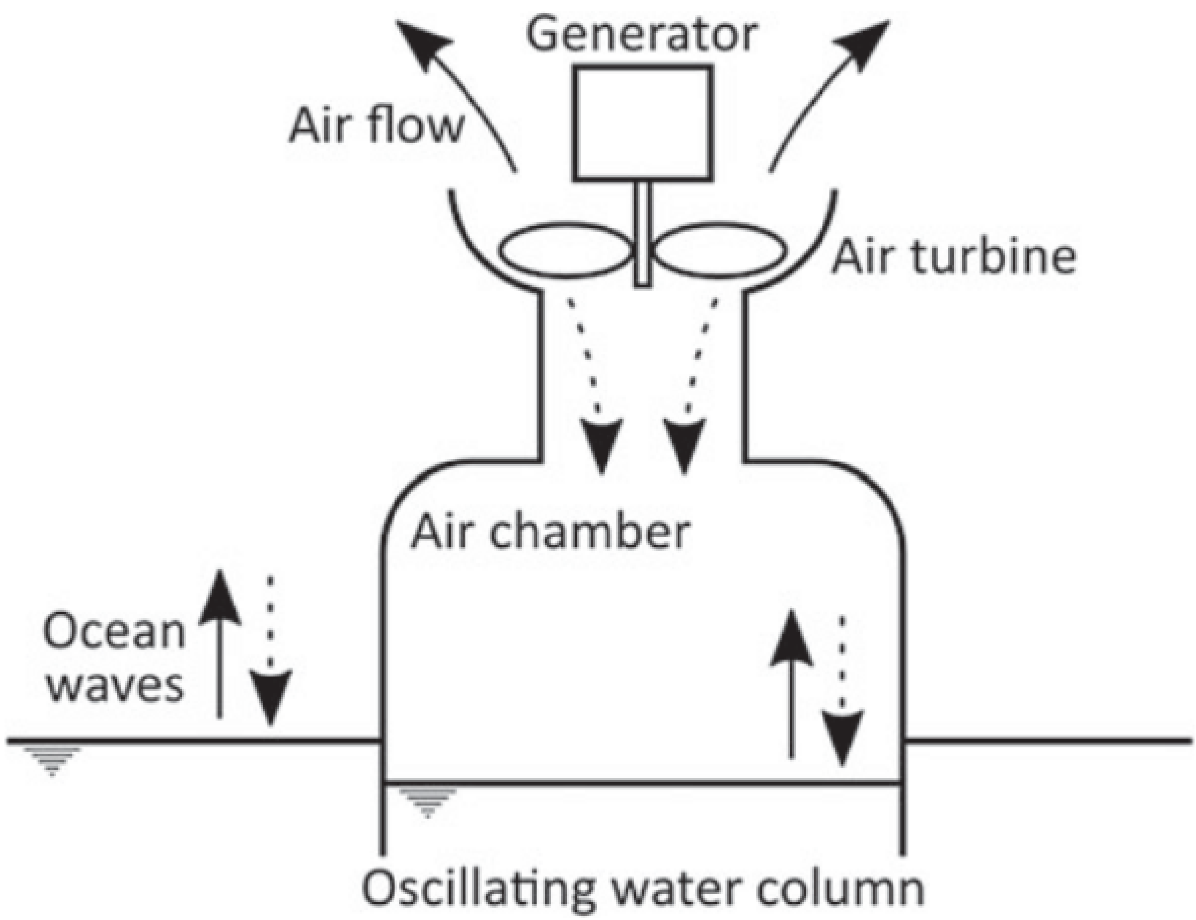

Fig. 3.5: Schematic of air turbine concept

The video clip below showcases the Halona PTO bench test apparatus at the University of Hawaii at Manoa. The large piston emulates the free surface in the air chamber, oscillating back and forth to drive an impulse turbine.

3.4 Hydraulic PTO Systems

- Common in point absorbers and attenuators
  - Linear vs rotational
- Translate mechanical energy into fluid motion
  - Drives a hydraulic motor connected to an electrical generator
- Well-suited for handling high loads at low speeds
- Complex and prone to maintenance issues

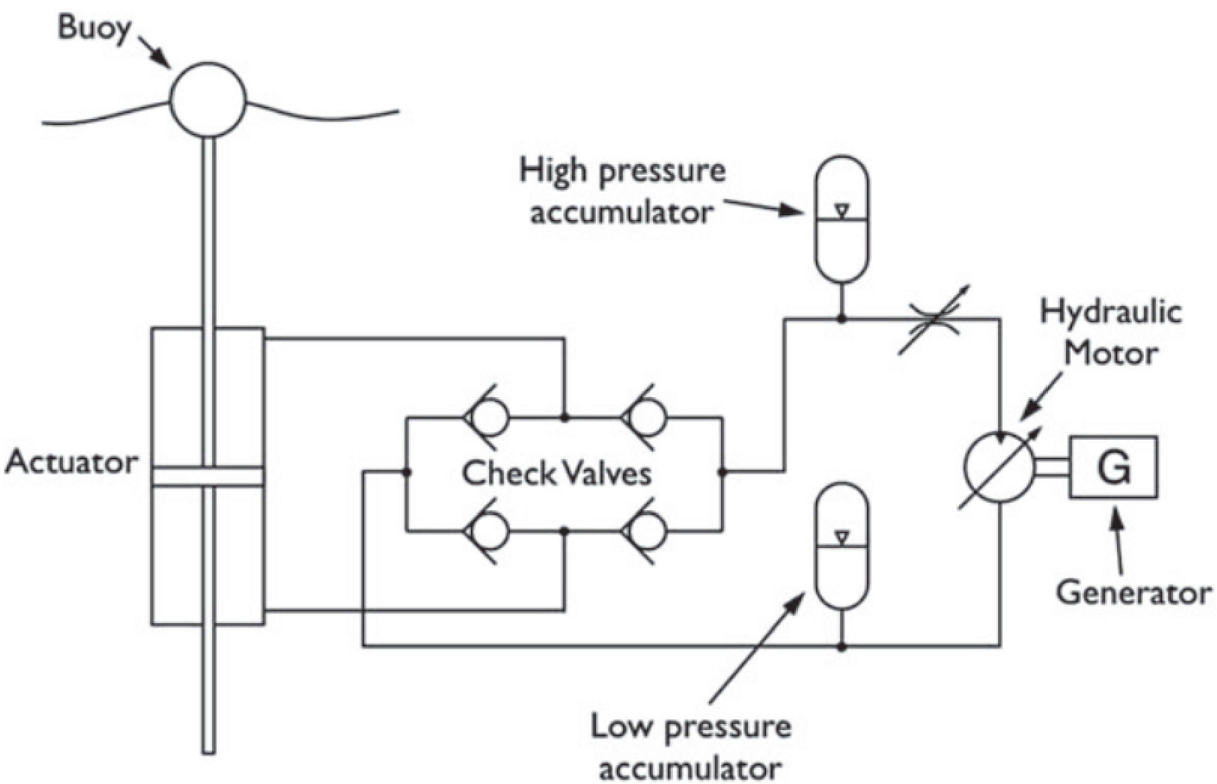

Fig. 3.6: Schematic of hydraulic PTO

3.5 Hydro Turbines

- Similar to use of hydraulic motor, but different working principle
  - Impulse vs Reaction
- Mature and highly efficient, with efficiencies exceeding 90%
  - Head vs flow

The video clip below showcases the HAWSEC PTO bench test apparatus at the University of Hawaii at Manoa. An electric actuator oscillates back and forth to drive a closed circuit hydraulic system connected to a Pelton turbine.

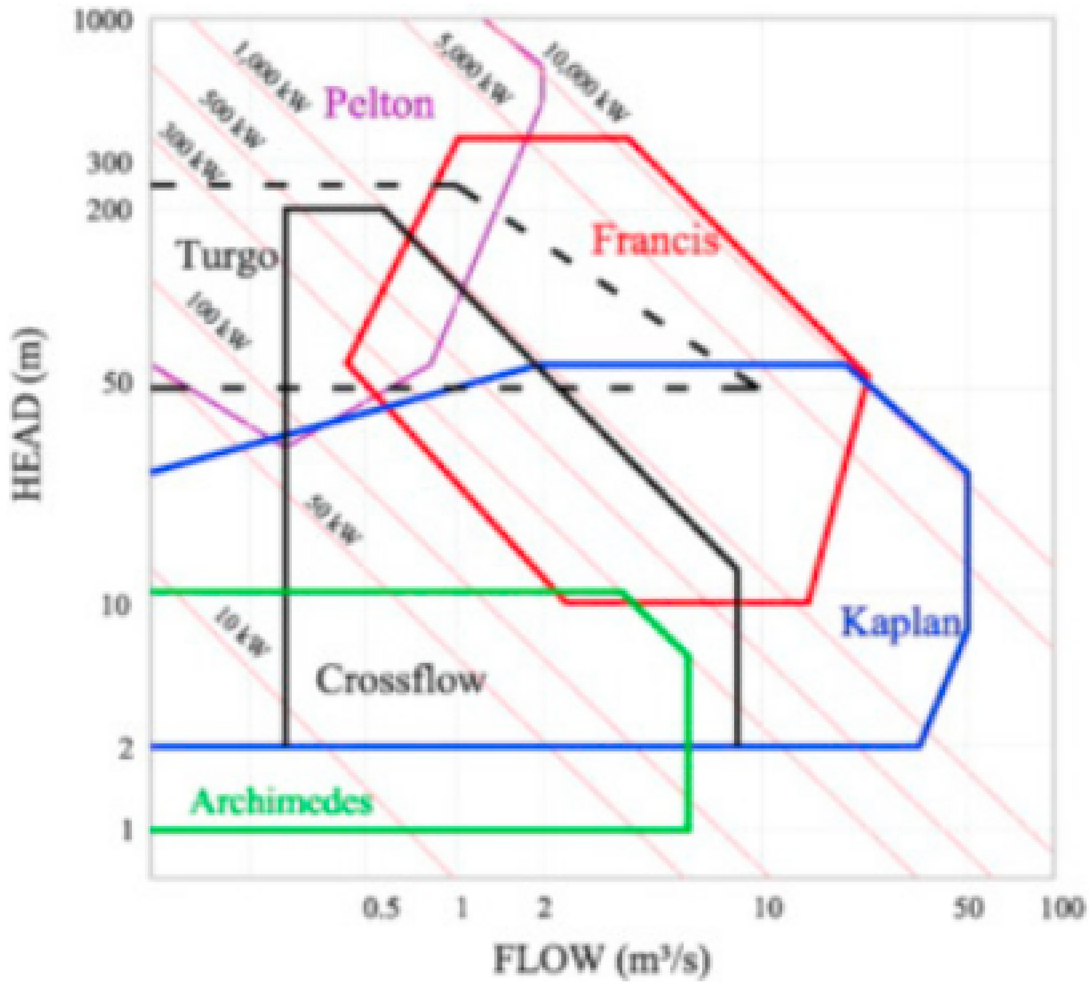

Fig. 3.7: Turbine designs for various flow regimes

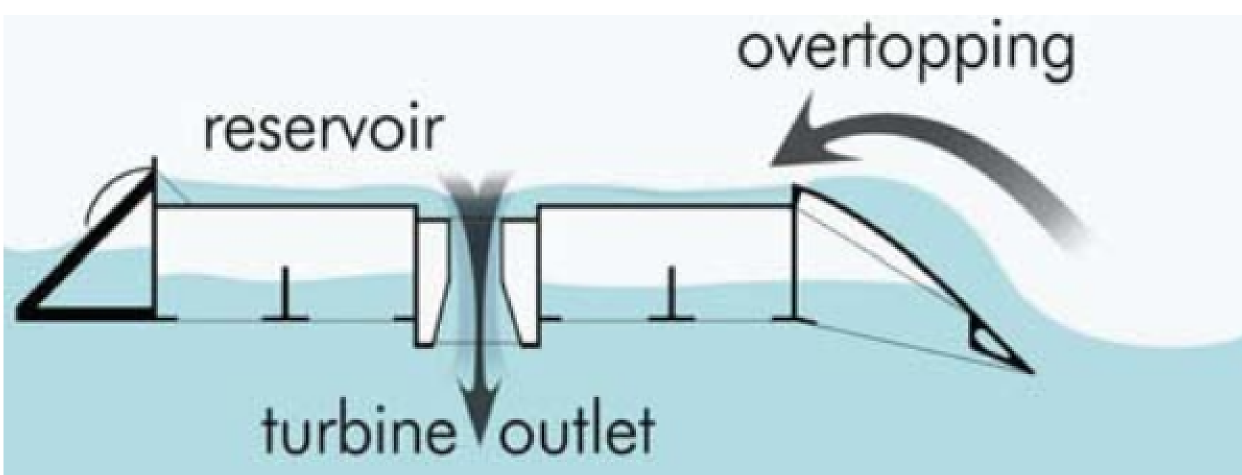

Fig. 3.8: Kaplan turbine application in Wave Dragon

3.6 Direct Mechanical Drive Systems

- Mechanical systems directly couple the motion of a WEC to an electrical generator
- Examples include systems with pulleys, cables, and gearboxes
- Fewer energy conversions mean higher efficiency
- Significant wear due to repeated load cycles
  - Needs more proof of concept…remember, waves different than wind

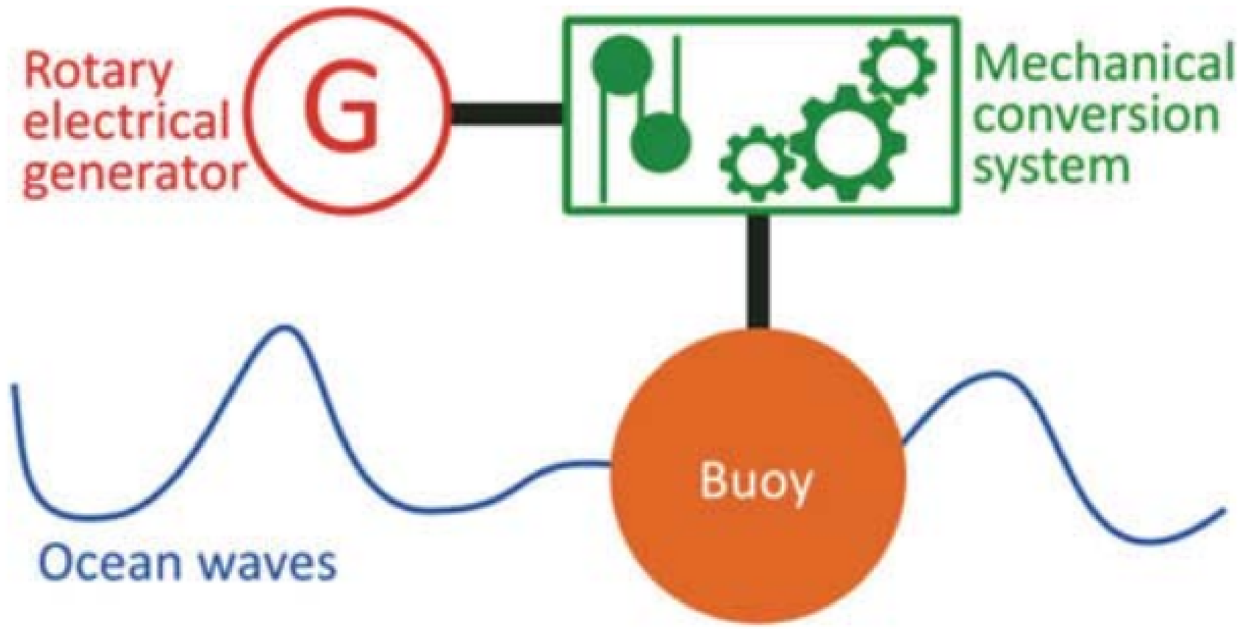

Fig. 3.9: Direct mechanical drive

3.7 Direct Electrical Drive Systems

- Similar to "Direct Mechanical Drive Systems" but no intermediate mechanical transfer
- Mostly developed in the field of power electronics
  - All conversions and smoothing done electrically
- Challenges include designing the structure to maintain fine tolerances between moving components.

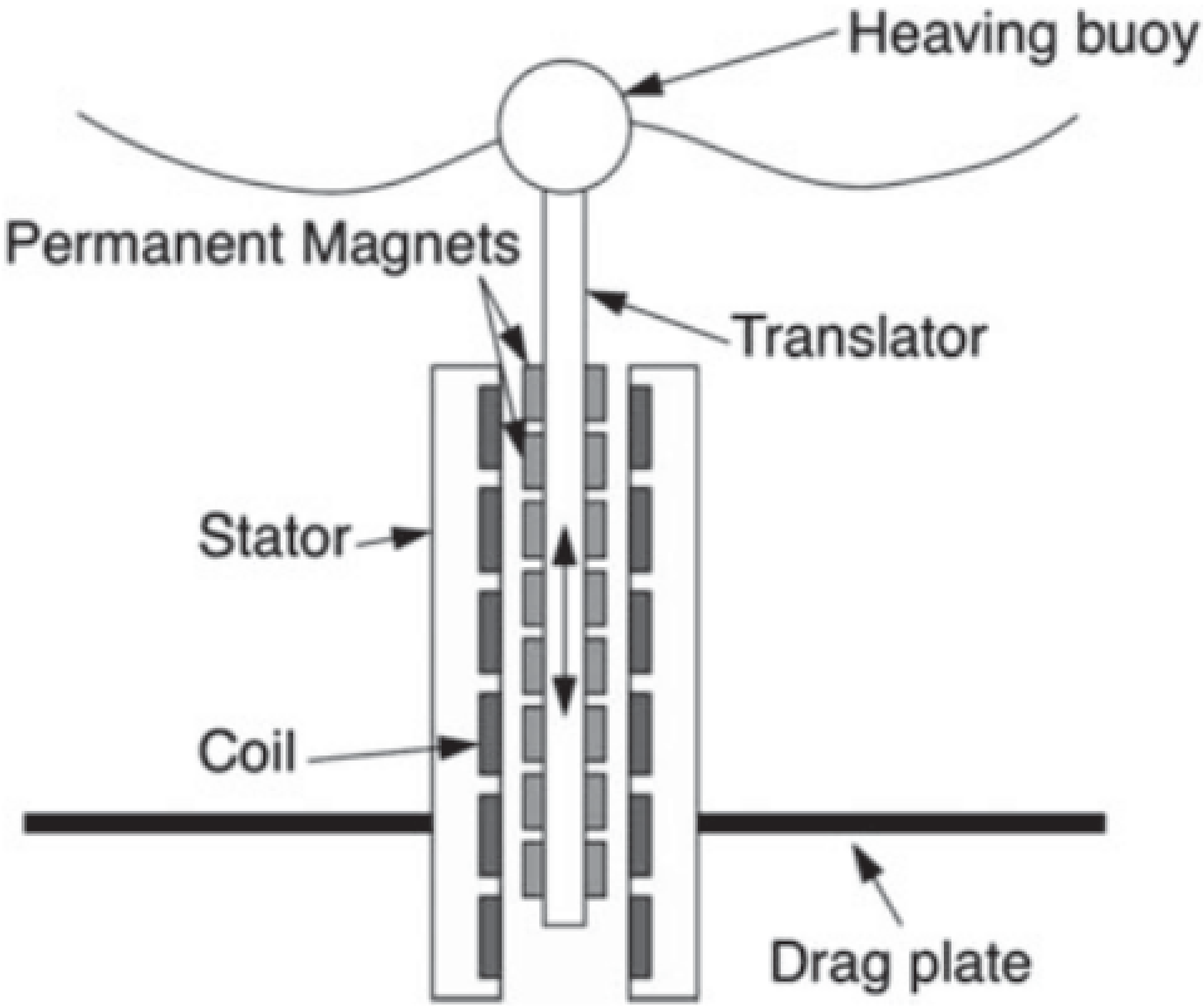

Fig. 3.10: Direct electrical drive

3.8 Control Strategies for PTO Systems

- Although designed to overlap with the wave spectrum, the device response spectrum is not a perfect overlap
  - Can target average, but spectrum itself is dynamic
    - Timescales?

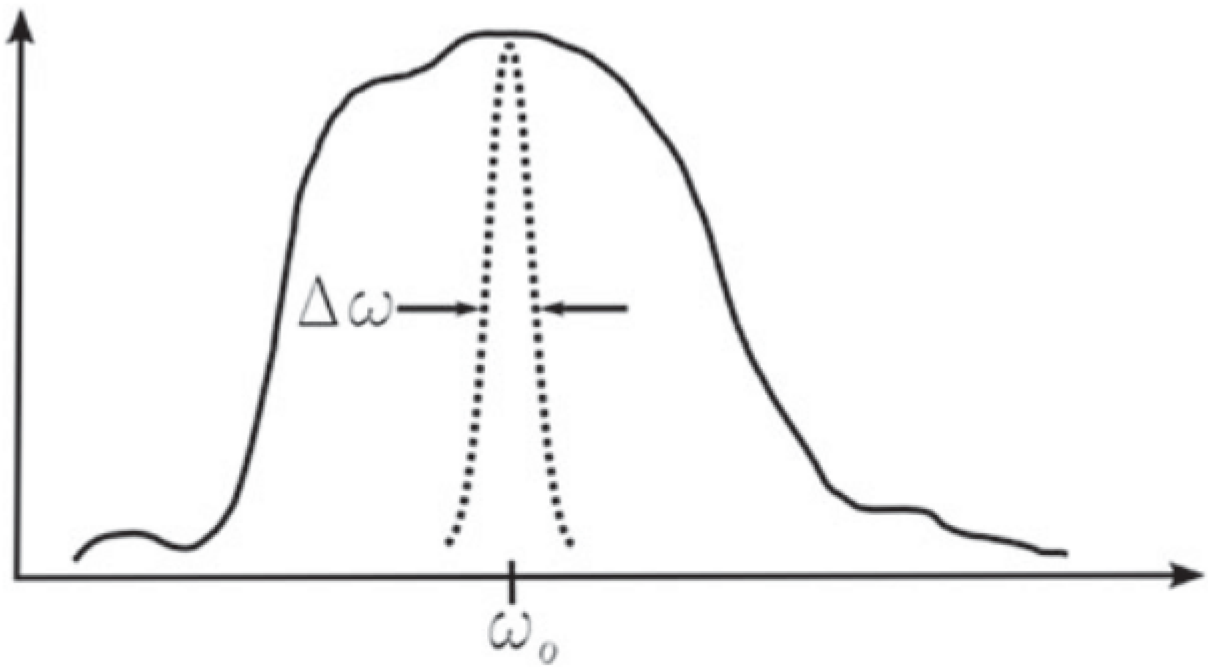

Fig. 3.11: Spectra comparison

- Control strategies can be implemented to manipulate the response
  - Recall the forces…inertia and restoring
  - Damping coefficient (F/V)
  - What's the trade off here?
  - Passive vs Active
- Latching Control: Holds the WEC in place during zero velocity and releases it to maximize energy absorption.
- Reactive Control: Actively adjusts the system's stiffness and damping to respond to wave frequencies.
- Both strategies require advanced prediction algorithms and responsive PTO systems.

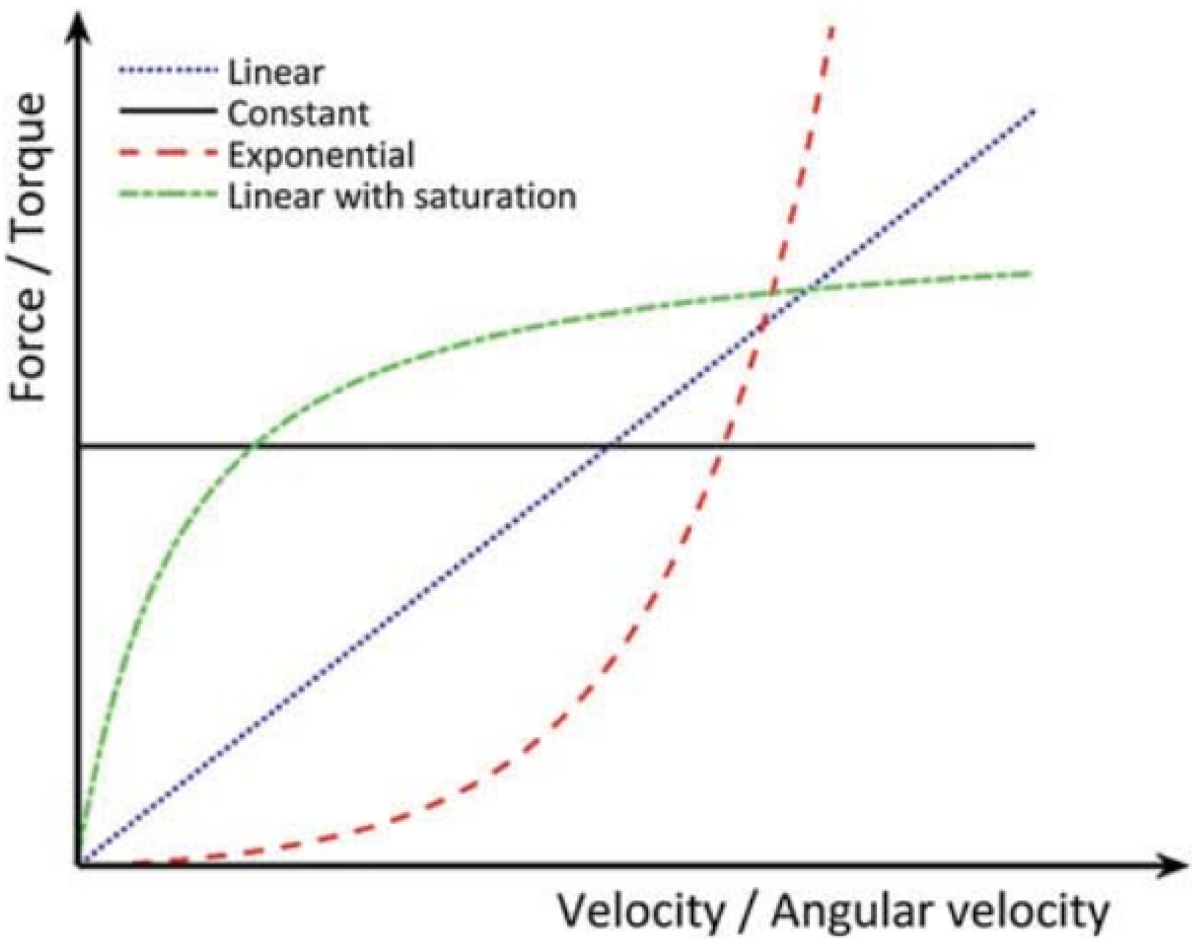

Fig. 3.12: Examples of different damping coefficients.

3.9 Summary and Conclusions

- PTO systems are a critical element in the success of WECs.
  - Need to understand the trade offs
- The choice of PTO system affects efficiency, cost, and reliability, directly influencing the economic viability of wave energy.
- Continued research and development in PTO systems and control strategies are needed to lower costs and improve performance.

CHAPTER

FOUR

CHAPTER 9: EXPERIMENTAL TESTING AND EVALUATION OF WECS

- Importance of experimental tests in validating WEC technologies.
- Testing environments: tank testing (controlled wet), test benches (controlled dry), and sea trials (uncontrolled wet).
- Different stages of WEC development require different testing approaches.

4.1 Overview of Test Campaigns

- Objectives of test campaigns: investigate and validate performance, structural integrity, and survivability.
- Example: Wavestar WEC development involved multiple test campaigns using models, prototypes, and test benches.
- Testing complexity increases with model size and environmental complexity.

4.2 Tank Testing

- Tank testing covers all stages of WEC development, from proof of concept to near-commercial devices.
- Key objectives: verify energy production, assess power performance, structural loads, and mooring forces.
- Tank tests typically use irregular waves to simulate realistic marine conditions.

4.3 Sea State Selection for Testing

- Sea states are representative wave conditions used for testing.
- Selected based on the most critical wave parameters (significant wave height Hs, and energy period Te).
- Example: Sea states used for Danish North Sea testing—selected to cover maximum energy production potential.

4.4 Testing Structural and Mooring Forces

- Tank tests help assess maximum structural and mooring forces under various sea states.
- Importance of testing under operational and design sea states to simulate real-world extreme conditions.
- Structural loads need to be verified for survivability.

4.5 Hydrodynamic Response of WECs

- Natural period of oscillation is key to understanding the response of WECs to wave action.
- Response Amplitude Operators (RAOs) describe how a WEC responds to different wave frequencies.
- RAOs can be measured in both regular and irregular waves.

4.6 Power Performance Evaluation

- Evaluation starts with measuring the absorbed power (Pabs) of the WEC.
- Capture Width Ratio (CWR) is a key performance metric (absorbed power per meter of wave front).
- Tank tests aim to develop a performance curve or surface for different wave conditions.

4.7 Scaling and Estimating Mean Annual Energy Production (MAEP)

- Tank testing results are scaled to estimate full-scale performance.
- Mean Annual Energy Production (MAEP) calculated using scaled sea states and capture width data.
- Importance of matching WEC design to peak energy production zones.

4.8 Scaling Considerations in Testing

- Froude's Model Law is used to scale data between model and full-scale WECs.
- Scaling influences hydrodynamic behavior, power production, and structural loads.
- Choosing an appropriate scaling ratio is key to optimizing testing results.

4.9 Sea Trials Overview

- Sea trials represent the final phase of WEC testing, exposing the device to uncontrolled real-world conditions.
- Sea trials assess performance, maintenance requirements, and operational capabilities.
- Example: Billia Croo test site for WECs.

4.10 Performance Assessment in Sea Trials

- Sea trials allow for refining performance metrics, including MAEP and Levelized Cost of Energy (LCoE).
- Data from sea trials is used to validate and adjust earlier testing results.
- Methodologies for sea trial assessment are under development (e.g., IEC 62600 standards).

4.11 Key Challenges in Experimental Testing

- Cost and time constraints are major challenges for both tank testing and sea trials.
- Optimizing test procedures is critical for gathering robust data within limited timeframes.
- Continued testing and innovation needed to improve WEC efficiency and reliability.

4.12 Summary and Conclusions

- Experimental testing is essential for the development and commercialization of WEC technologies.
- A comprehensive approach combining tank testing, test benches, and sea trials is necessary to validate WECs.
- Testing informs both technical development and economic viability assessments.