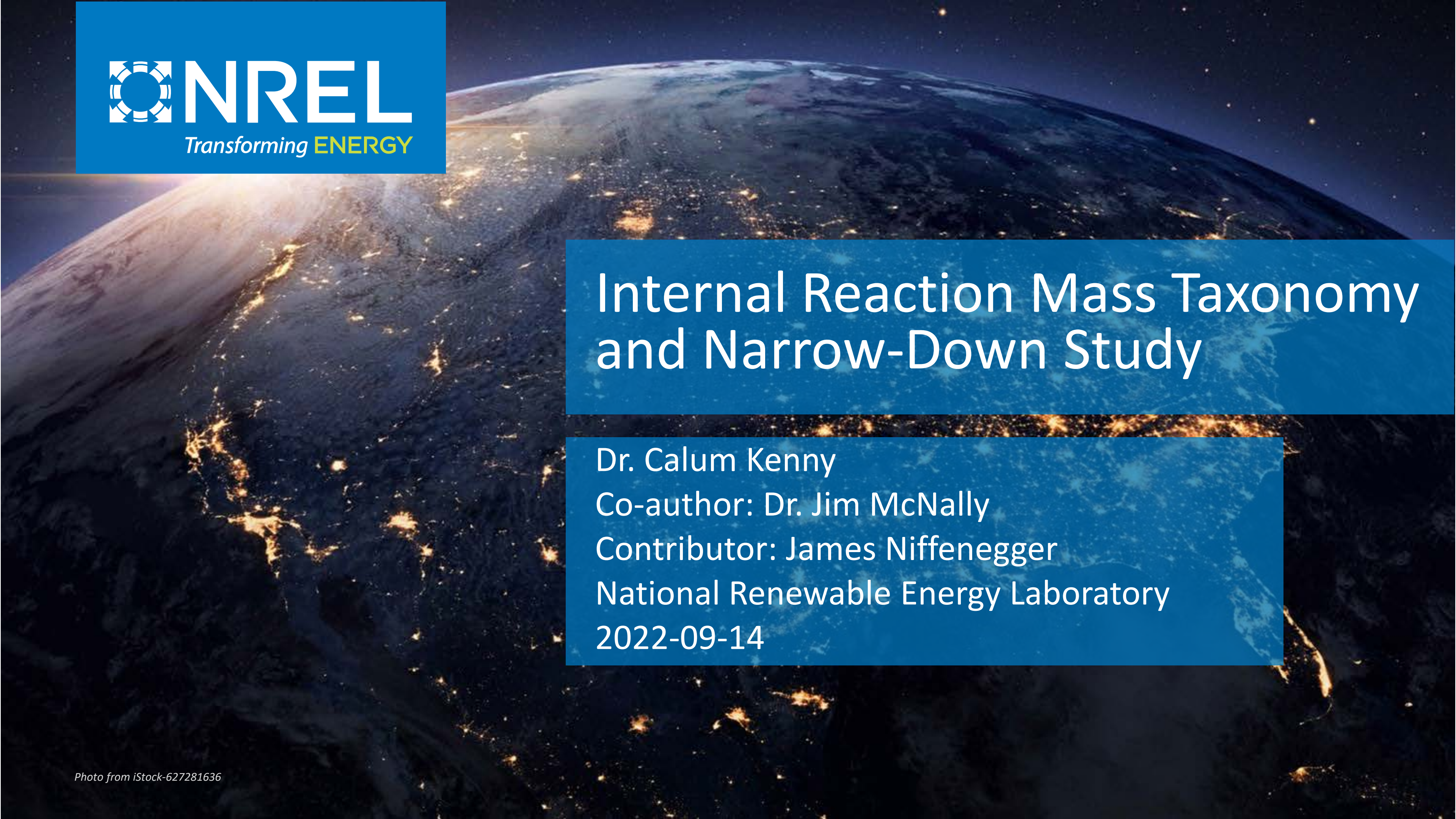

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Internal Reaction Mass Taxonomy and Narrow-Down Study

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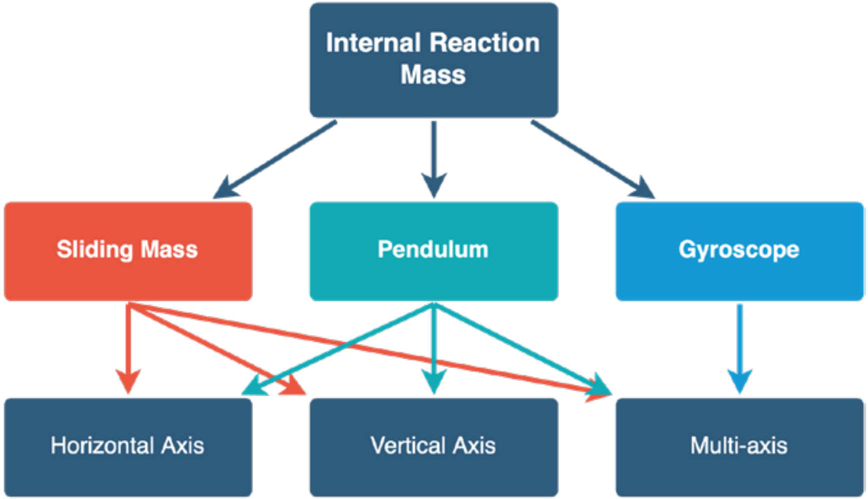
Introduction – Background

- Powering the Blue Economy™ Power at Sea initiative
  - Seeking to power ocean observation and navigation applications.
- Aim
  - Ascertain the feasibility of powering ocean observation applications using internal reaction mass (IRM) technologies
  - Identify the most promising candidate IRM mechanisms within the reviewed literature for further investigation.

Image from LiVecchi et al. (2019)

Introduction – Taxonomy

- IRM wave energy converter (WEC):
  - Reacts against the inertia of a moving mass suspended within the WEC structure.
- IRM WEC device categories:
  - **Sliding mass:** Devices that use a reaction mass that translates linearly.
  - **Pendulum:** Devices that use a reaction mass that rotates irregularly about an axis.
  - **Gyroscope:** Devices that use a continuously spinning flywheel reaction mass.
- Reaction mass axes of motion
  - Horizontal, vertical or multi-axis.

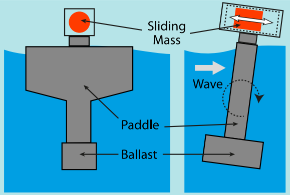


Internal Reaction Mass Categories and Axes of Operation

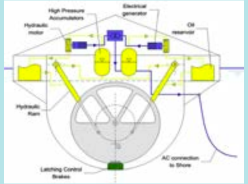
Introduction – IRM WEC Examples

Sliding Mass | **Pendulum** | **Gyroscope**

Horizontal Axis

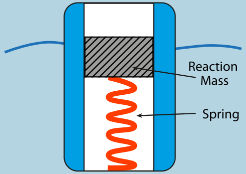


Adapted from Falcão (2010)

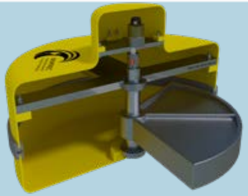


Cordonnier et al. (2015)

Vertical Axis



Adapted from French (2006)

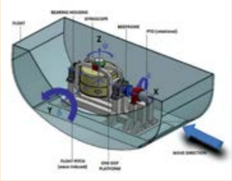


With permission Boren et al. (2017)

Multi-Axis

Aggidis and Taylor (2017)

Crowley et al. (2018)



Cagninei et al. (2015)

Methodology 1 – Power Density

- Compiled device database of 41 unique IRM device prototypes
  - Extracted average, rated, and peak power information
  - Used total mass as best representative parameter for device size and scale.
- Gathered representative application data and created three scenarios:

1. Distributed data collection node consisting of small, lightweight buoy with small sensor payload (~3–5 PCB sensors), optimized for extremely low power consumption. Periodic data collection and transmission using telemetry.

2. Midsize ocean observation buoy that continuously samples small to medium payload of sensors (~5 individually packaged sensors). May have solar capacity to extend operational time.

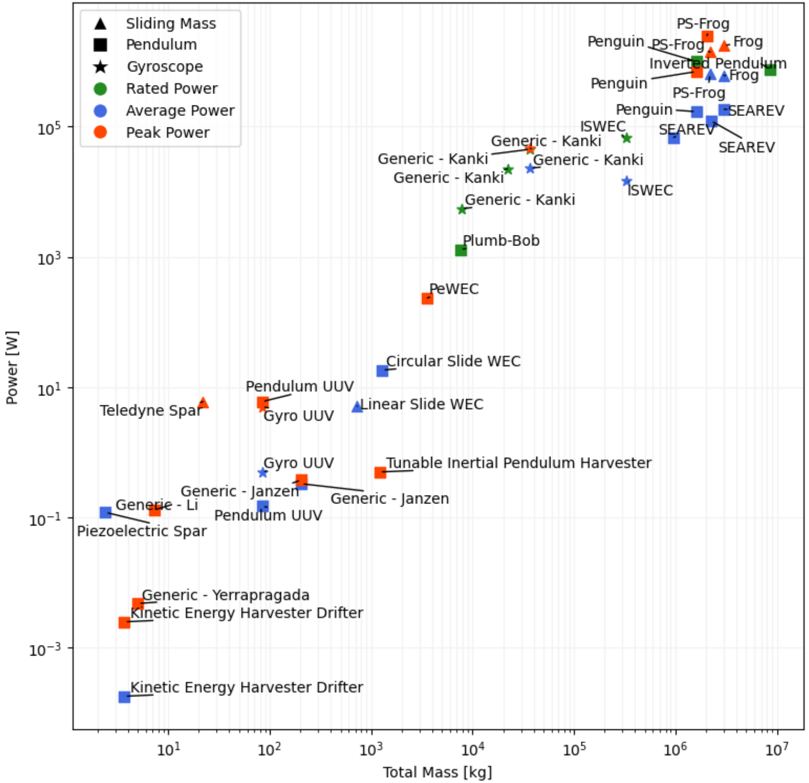
3. Floating platform offering space for midsize to large sensor payload (~10 sensors). Typically large solar capacity to provide continuous power to sensors and telemetry.

Application Scenario	**Power Consumption**		**Payload (20% of total mass)**	
	Min [W]	Max [W]	Min [kg]	Max [kg]
1. Data collection node	0.01	0.10	1	5
2. Ocean observation buoy	0.10	1.00	5	25
3. Large sensor platform	5.00	100	25	250

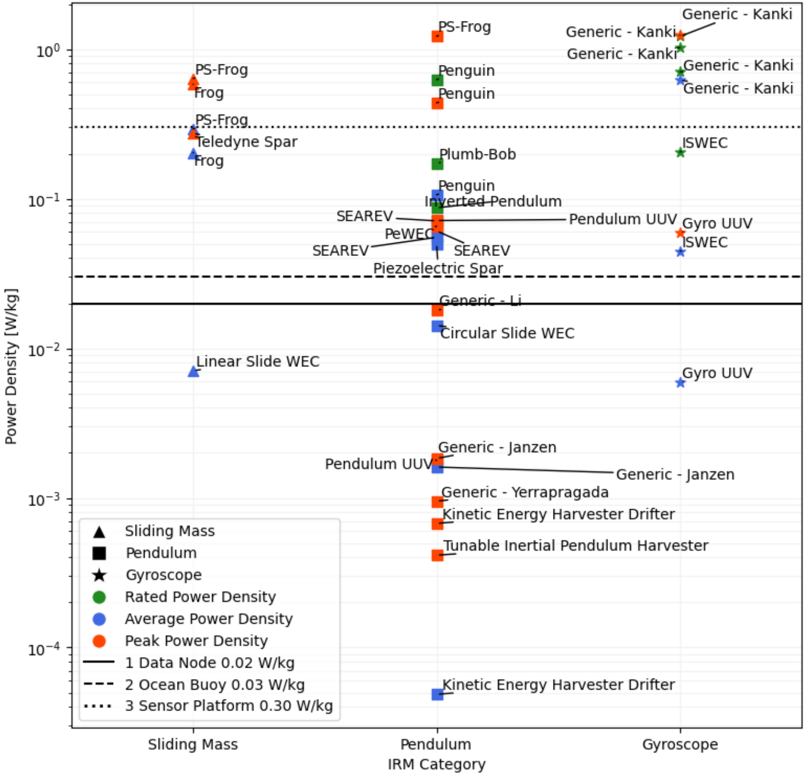
Application Scenario	**Power Density**		
	Min/Min [W/kg]	Max/Max [W/kg]	Avg [W/kg]
1. Data collection node	0.01	0.02	0.02
2. Ocean observation buoy	0.02	0.04	0.03
3. Large sensor platform	0.20	0.40	0.30

Power consumption, payload, and power density requirements of each application scenario. Power density calculated assuming 20% total mass available as payload.

Results 1 – Power Density



Plot of rated, average, or peak power output vs. total device mass.



Plot of device power density vs. device category.

Results 1 – Power Density

- Candidate devices

Ranking	Device	Device Type
1	Kanki Dual Gyro	Dual gyroscopic device
2	PS Frog	Horizontal sliding mass
3	Penguin	Vertical pendulum
4	Frog	Vertical sliding mass
5	Teledyne Spar	Vertical sliding mass
6	ISWEC	Dual gyroscopic device
7	Plumb-Bob	Horizontal pendulum
8	Inverted Pendulum	Horizontal pendulum
9	Pendulum UUV	Horizontal pendulum
10	SEAREV	Horizontal pendulum

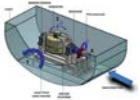
- Limitations
  - Known issues with spring sagging and end-stops in vertical sliding mass devices
  - Power reporting from various research articles is inconsistent
  - Capacity factor and nominal power are important but typically unavailable
  - Many papers lack information entirely.

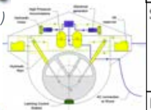
Methodology 2 – Device Matrix

- Modify candidate devices list by:
  - Removing vertical sliding mass devices
  - Exchanging similar devices in favor of those with greater literature or history of development
  - Adding promising mechanisms not included in power density study
  - Including mechanisms to fully represent IRM technology space.
- Develop device selection criteria
  - Power density
  - Ability to prototype
  - Self-start capability
  - Control system
  - Reliability and maintainability
  - Mooring requirements
  - Directionality.
- Study conducted for 1-W to 10-W device.

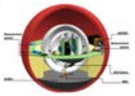
Results 2 – Device Matrix

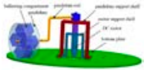
- Applied weighted scoring system to obtain percentage score.

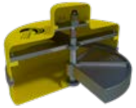

Cagninei et al. (2015)


Cordonnier et al. (2015)


Yang (2011)


Carandell (2020)


Ding (2018)


Boren et al. (2017)


Crowley et al. (2018)

Device	Reaction Mass Category	Axis of Operation	Power Density	Prototypability	Self-Start Capability	Control System	Reliability and Maintainability	Mooring Requirements	Directionality	Score	Ranking
			25%	20%	15%	10%	10%	10%	10%		
ISWEC	Gyroscope	Multi-Axis	5	2	1	3	2	4	2	58%	6
SEAREV	Pendulum	Horizontal Axis	4	3	3	2	4	2	2	61%	5
Plumb-Bob	Pendulum	Horizontal Axis	2	3	3	2	5	4	1	55%	7
Kinetic Energy Harvester Drifter	Pendulum	Horizontal Axis	1	4	4	5	4	5	4	69%	1
Tunable Inertial Pendulum Harvester	Pendulum	Vertical Axis	2	4	3	3	3	4	5	65%	3
VAPWEC	Pendulum	Vertical Axis	3	4	3	3	3	1	5	64%	4
WITT	Pendulum	Multi-Axis	3	4	4	4	2	3	4	69%	1

Discussion

- Power densities of devices not fully understood due to poor comparability between papers
  - Hydrodynamic benchmarking study of candidate devices best place to start.
- Power density study suggests IRM WECs can sufficiently power low-power optimized distributed data collection nodes; however, they struggle to power larger sensor systems on their own
  - A separate, nonintegrated WEC may be best for powering larger platforms
  - Innovative materials may also provide a means of increasing power density at these small scales.

Conclusion

- Hydrodynamic benchmarking study will enable a fairer comparison of the technology space.
- Experimental characterization of horizontal or multi-axis pendulums can provide a sound choice for initial prototyping.
- Designing a WEC separate to the marine infrastructure it supports allows one to escape the power density trap.

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