KONFLOT

Energía berriztagarri flotatzaileen kontrol diseinu bateratua

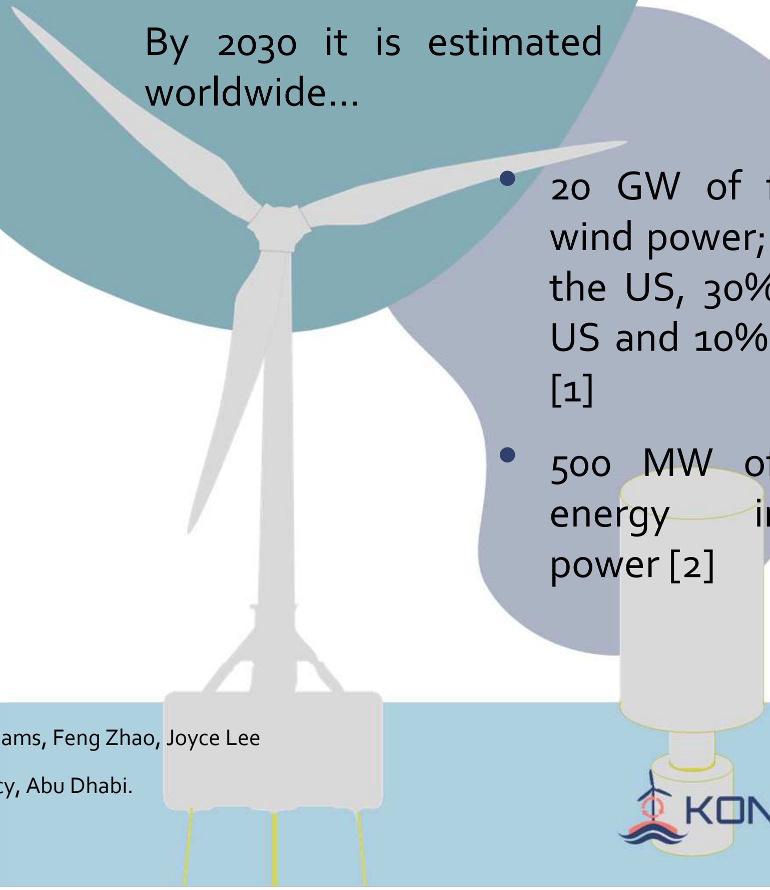
Control co-design for floating renewable energy

Eider Robles & Markel Peñalba

Proyecto subvencionado por el Departamento de Desarrollo Económico, Sostenibilidad y Medio Ambiente del Gobierno Vasco (Programa ELKARTEK 2022)
Eusko Jaurlaritzaren Ekonomiaren Garapen, Jasangarritasun eta Ingurumen Saila (ELKARTEK 2022 Programa) diruz lagundutako proiektua
Project funded by the Department of Economic Development, Sustainability and Environment of the Basque Government (ELKARTEK 2022 Programme)

CONTEXT

- **Floating wind** is a technology that will allow the efficient exploitation of wind potential in deeper waters and, therefore, will be able to foster rapid growth in the future offshore wind market.
- **Wave energy** is a developing technology that is mainly in the prototype and demonstration phase.



By 2030 it is estimated worldwide...

- 20 GW of floating wind power; 60% in the US, 30% in the US and 10% in Asia [1]
- 500 MW of wave energy installed power [2]

[1] Global Wind Energy Council (GWEC) (2022), *GLOBAL OFFSHORE WIND REPORT 2022,* Rebecca Williams, Feng Zhao, Joyce Lee

[2] IRENA (2020), *Innovation outlook: Ocean energy technologies*, International Renewable Energy Agency, Abu Dhabi.

DESIGN PARALELISM

Current design

Stable design, without considering the control

Control co-design

Control system

Unstable design: lighter

CURRENT DESIGN METHODOLOGY

- Sequential and independent desaign
- Each steps limits the posibilities of the next
- Control takes part in the end, once the design is finished

Technically impossible for a multidisciplinary system to be fully optimized if the interactions between the subsystems are not considered in the design.

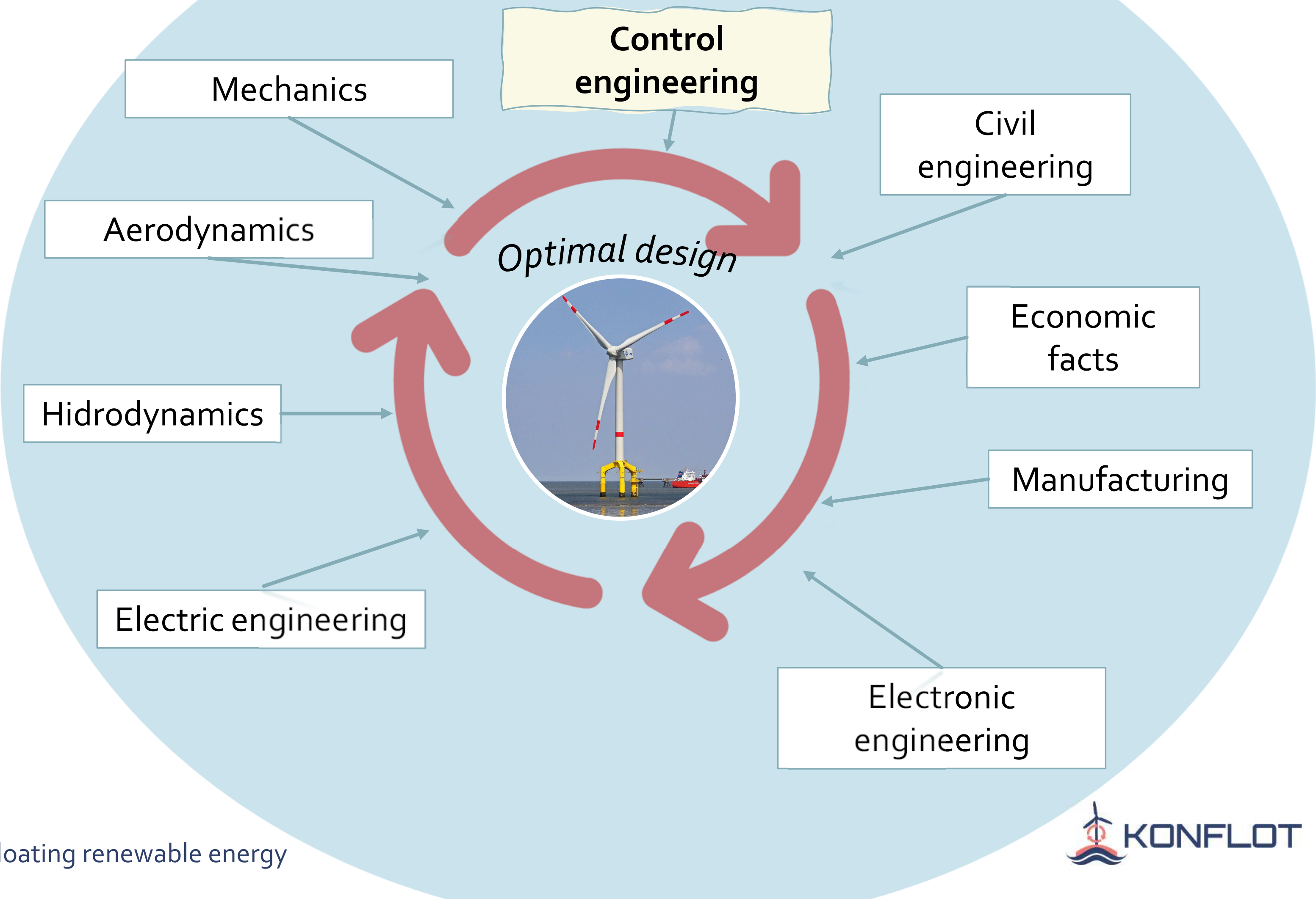
NEW DESIGN METHODOLOGY

Different disciplines work concurrently from the start

~~**Sequential**~~

~~**Independent**~~

Emphasis on interactions between subsystems and control paradigms



OPORTUNITY AND CHALLENGE

According to the main CCD researcher, Mario García-Sanz [1], Program director at ARPA-E (Advanced Research Projects Agency-Energy, USA), control codesign techniques could help to:

- Reduce mass of the structures up to 50%
- Reduce losses up to 15%
- Reduce OPEX up to 15%

Globally reducing the LCOE (Levelized Cost Of Energy) up to 45%

[1] Mario Garcia-Sanz Program director ARPA-E, "Control Co-Design for Wind/Tidal/Wave Energy Systems", 2018

OBJECTIVES

Establish a design methodology that considers, from the early design phases, the different subsystems, their dynamics and interactions, and the performance of the controls available in the floating renewable generation devices..

- Identification of CCD techniques applicable to floating wind power and wave energy collectors
- Selection of variables with the greatest impact in the design of the subsystems and definition of the objective metrics to apply CCD
- Definition of a CCD methodology based on numerical models, innovative control strategies for different subsystems and optimization algorithms
- Validation of the methodology and tools by applying them to two use cases: (i) floating wind and (ii) wave energy

EXPECTED RESULTS

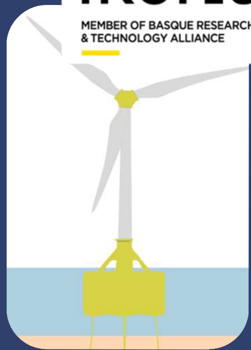
- ✓ A **methodology** to apply CCD techniques to floating wind and wave energy collectors.
- ✓ **Optimization tools** and algorithms that allow the interaction between the dynamics of the different subsystems.
- ✓ **Advanced controls** for floating wind and wave energy, which are integrated into the CCD process.

PARTNERS

Project coordination and management — tecnalia

tecnalia

Control co-design of floating wind



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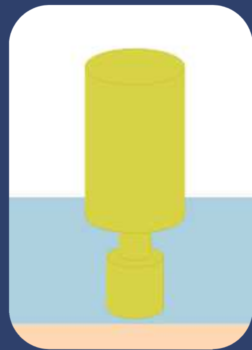
Mondragon Unibertsitatea — Goi Eskola Politeknikoa

Control co-design of wave energy



Universidad del País Vasco — Euskal Herriko Unibertsitatea

Control strategies for its application in co-design

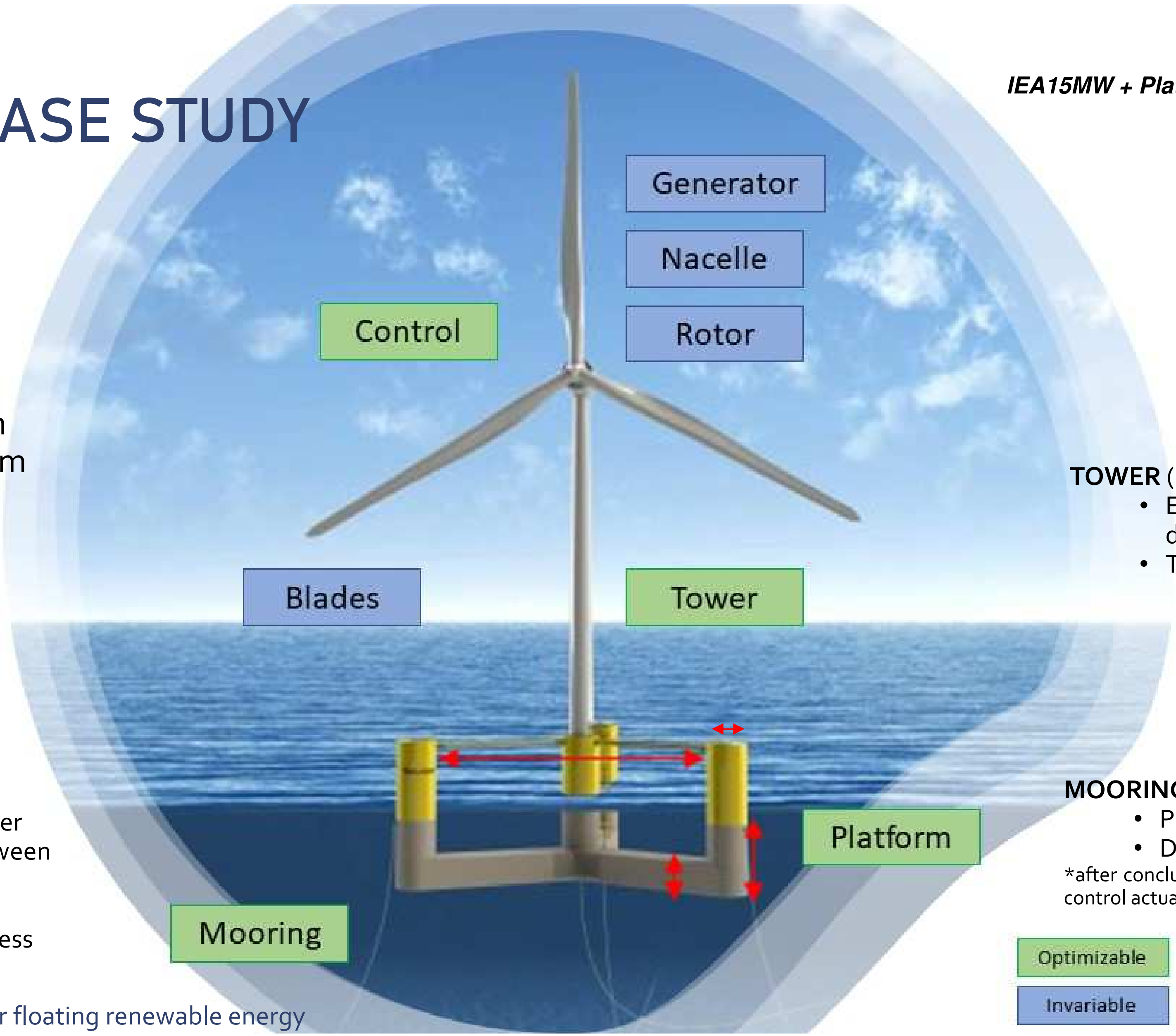
Co-optimization strategies and algorithms — bcam (basque center for applied mathematics)

Cluster Energía (Basque Energy Cluster) — Communication and dissemination

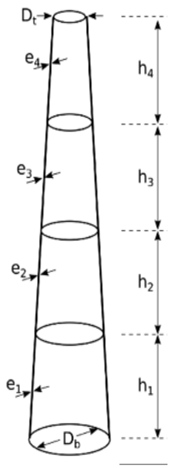
FOWT CASE STUDY

IEA15MW + Plataforma Umaine VolturnUS-S

SITE: 5West of Barra – Scotland
Hs = 15,60 m .
Extreme metocean conditions d = 100 m



TOWER (2xn sections)
- External diameter
- Thickness



PLATFORM (4)
- Column diameter
- Distance between columns
- Columns high
- Pontoon thickness

MOORING (2)*
- Pretension
- Diameter

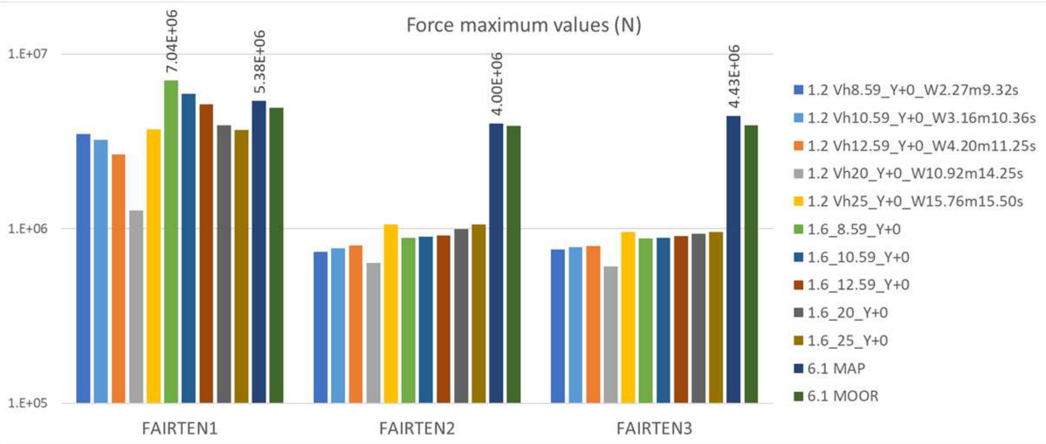
*after concluding that the design governs it during control actuation

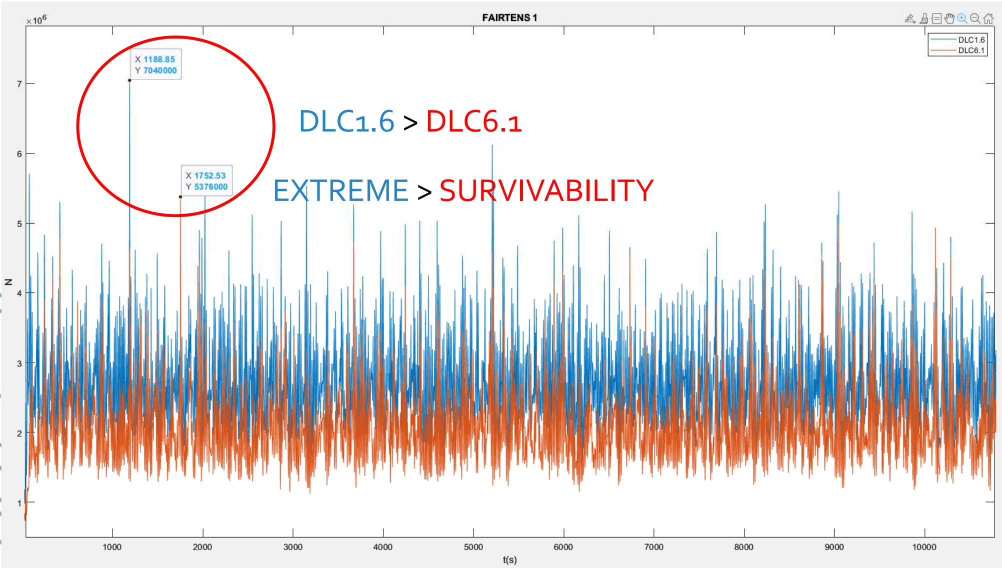
Optimizable

Invariable

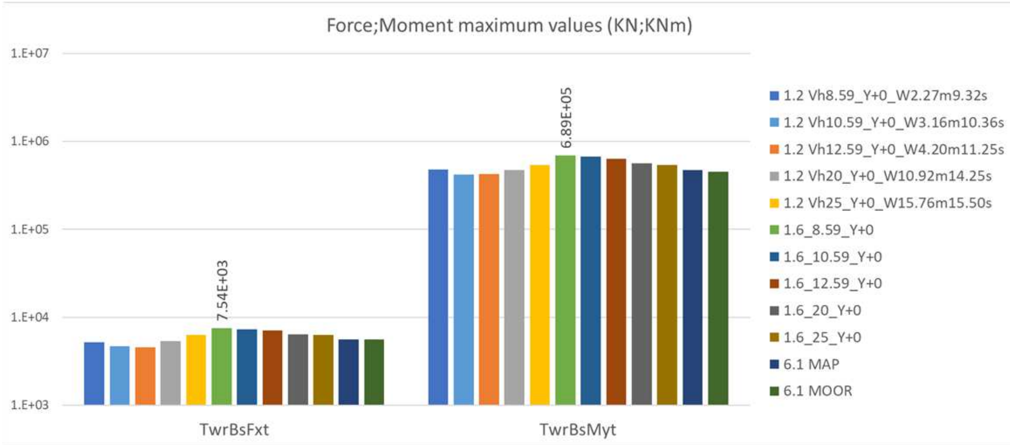
LOAD CASES

- FORCES IN FAIRLEADS

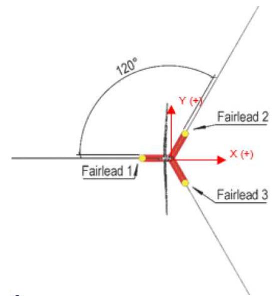




- FORCES/MOMENTS IN TOWER BASE



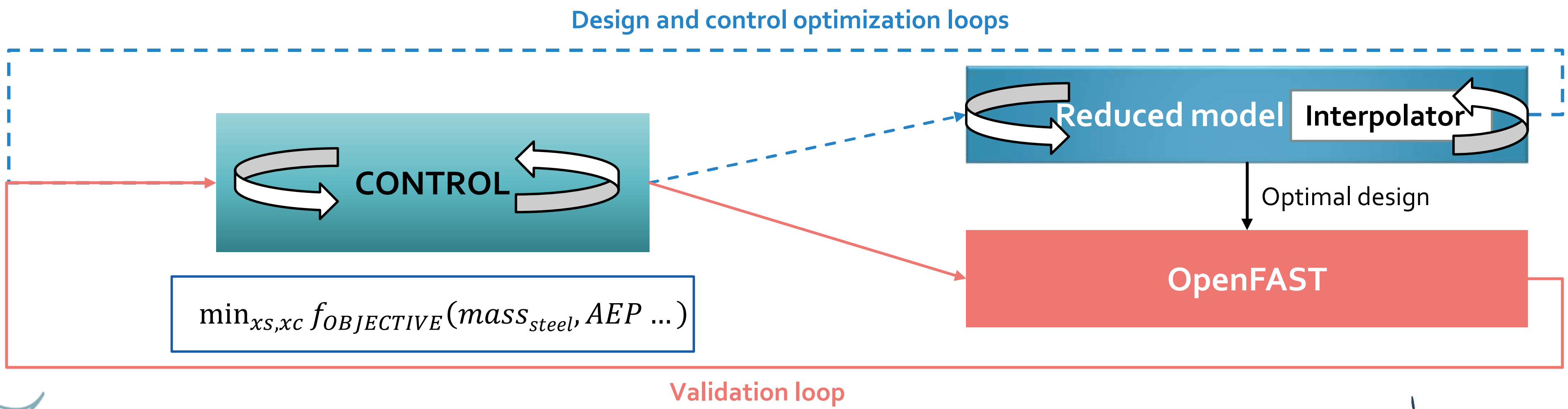
- DLC1.6 has máximums in FAIRTEN1 → Mooring subsistem must be in co-design
- To run the entire DLC set according to the norm for its validation and subsequent comparison against



DEVELOPMENT OF DESIGN AND OPTIMIZATION TOOL

For coupled dynamic simulation, optimization and evaluation of the system, allowing the use of different controllers and variables to be optimized.

For **optimization**, a **reduced model** of the system is used that captures the interactions with the controller design.
Once an optimized system has been reached, **OpenFAST** is used for **validation,** so that the design is validated in a software widely used by the industry with all DoF. It represents the real system.

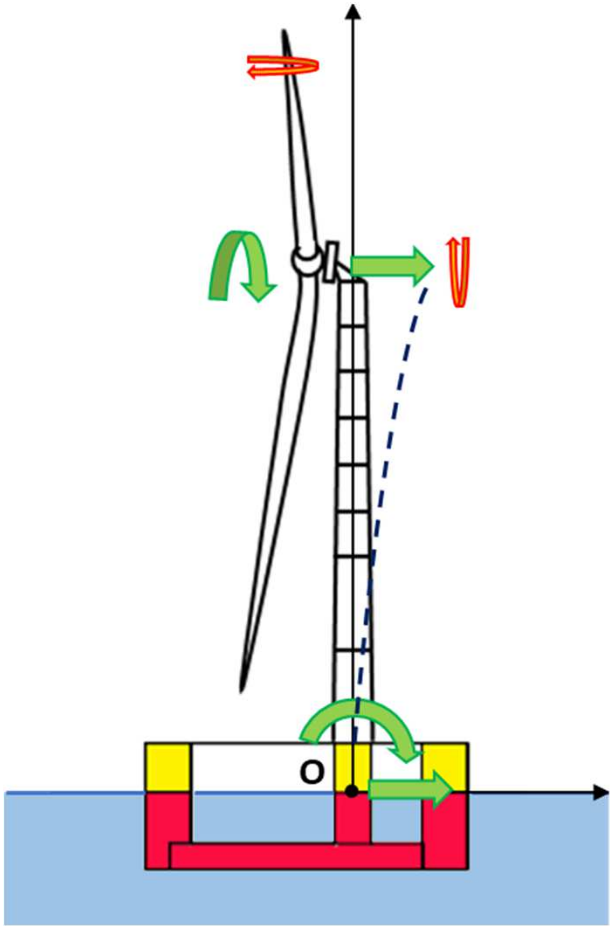


REDUCED MODEL

The **hydrodynamics** of the model consider first order hydrodynamics and Morison elements have been added to represent second order drag forces.

Aerodynamics is represented by Thrust and Power coefficients obtained from BEM theory.

The **mooring** system is represented by the catenary equation.

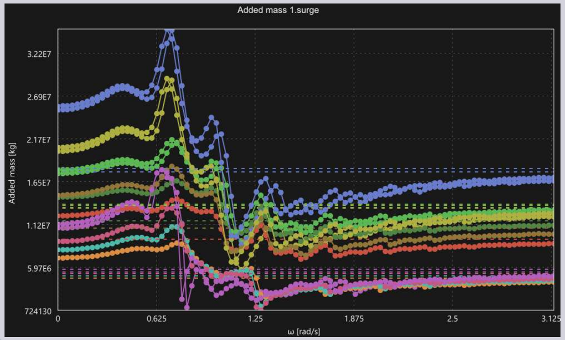


Degrees of Freedom

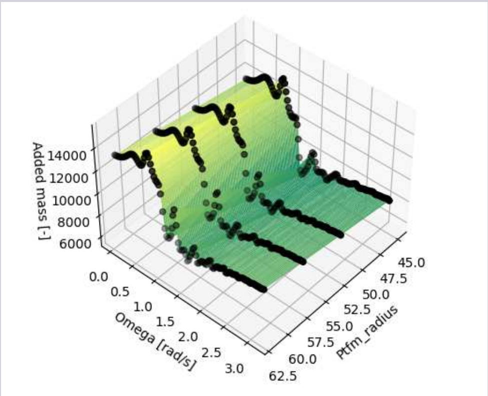
- Surge
- Pitch
- 1st bending mode of the tower in fore-aft
- Rotor speed
- Pitch actuator
- Torque actuator

REDUCED MODEL: Inteligent interpolator

Geometric variations of the platform → Recalculate hydrodynamic matrices → High computational cost



<u>Example</u>: Added mass in surge



Estimation of hydrodynamic parameters using data-based techniques

- ✓ 4D Interpolation
- ✓ Non-lineal regresion:
  - ✓ Polynomial (4D)
  - ✓ Machine-learning based

CONTROL STRATEGY

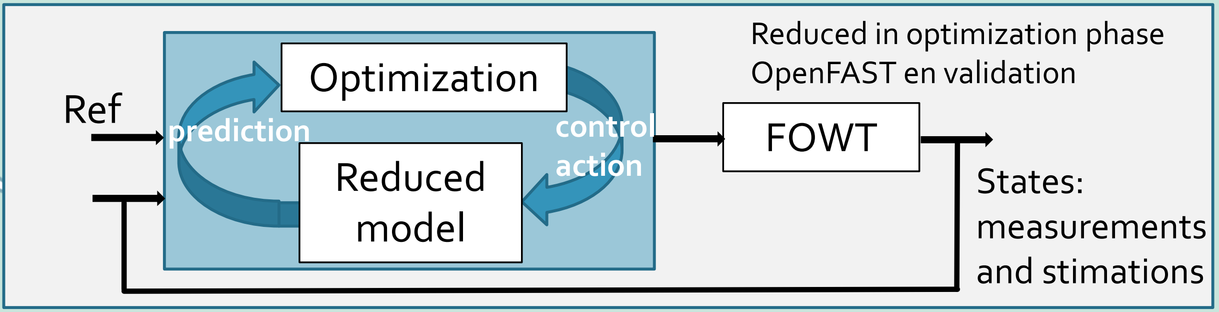
Objectives

- Maximum power extraction
- Reduce loads to allow optimization of subcomponent design

Blade Collective Control

Nonlinear Model Predictive Control (NMPC)

- Optimal control, based on previous work [2]
- Ability to anticipate disturbances

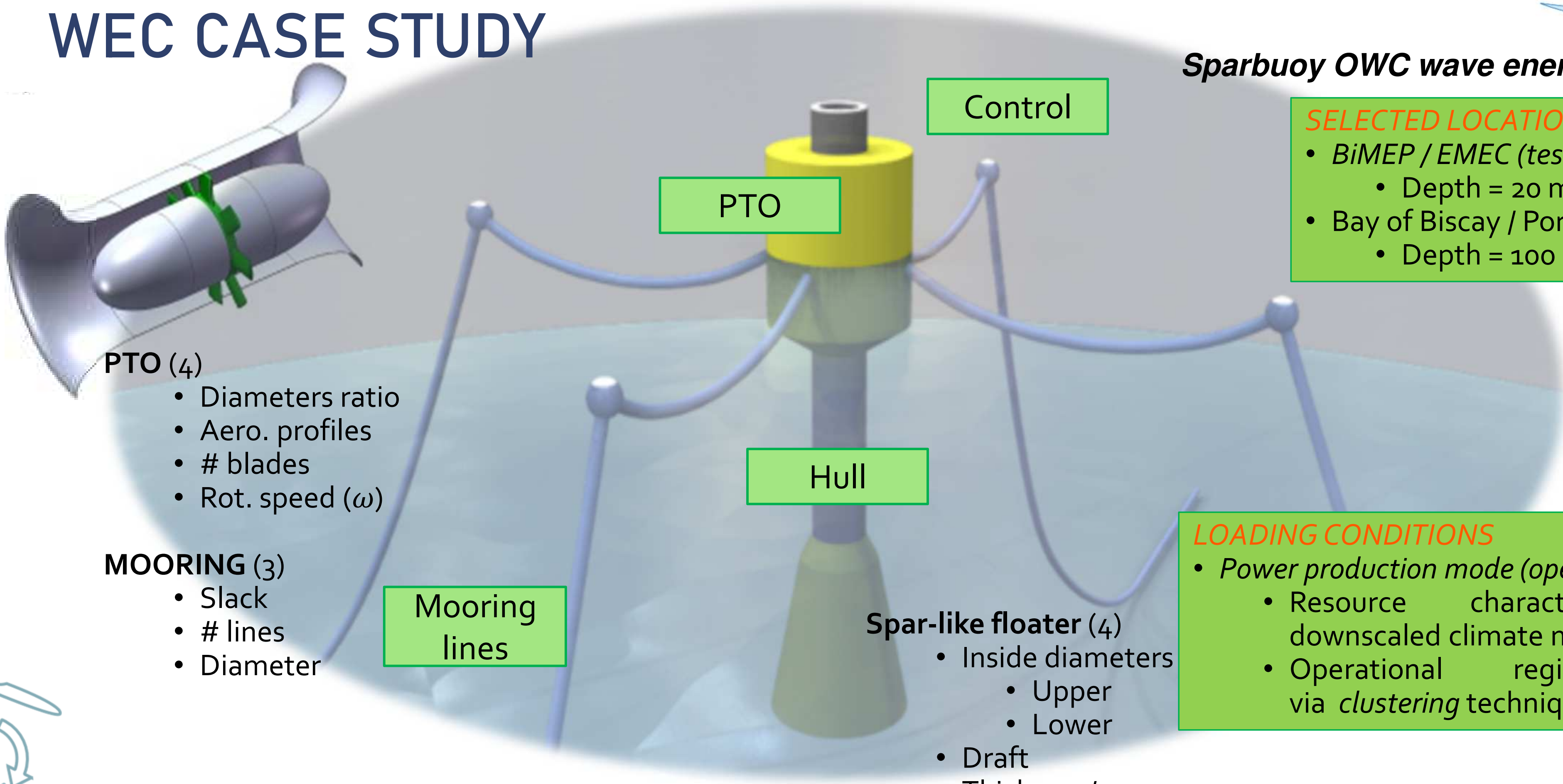


- Flexible tool → different options
  - NMPC with the same number of degrees of freedom of the plant with Feedback from all states
  - NMPC as power regulator together with additional loops that reduce movements (e.g. tower damper)
  - NMPC as an additional help to the turbine base controller (in anticipation of the difficulty of accessing the controller of a real turbine)
  - Base control with PI controllers
  - Allows co-design with other control strategies

[2] Javier López-Queija, Eider Robles, Josu Jugo, Santiago Alonso-Quesada, Review of control technologies for floating offshore wind turbines, Renewable and Sustainable Energy Reviews, Volume 167, 2022, 112787, ISSN 1364-0321,

WEC CASE STUDY

Sparbuoy OWC wave energy converter



SELECTED LOCATIONS:
- *BiMEP / EMEC (testing platforms)*
  - Depth = 20 m
- Bay of Biscay / Portugal (N. Atlantic)
  - Depth = 100 m

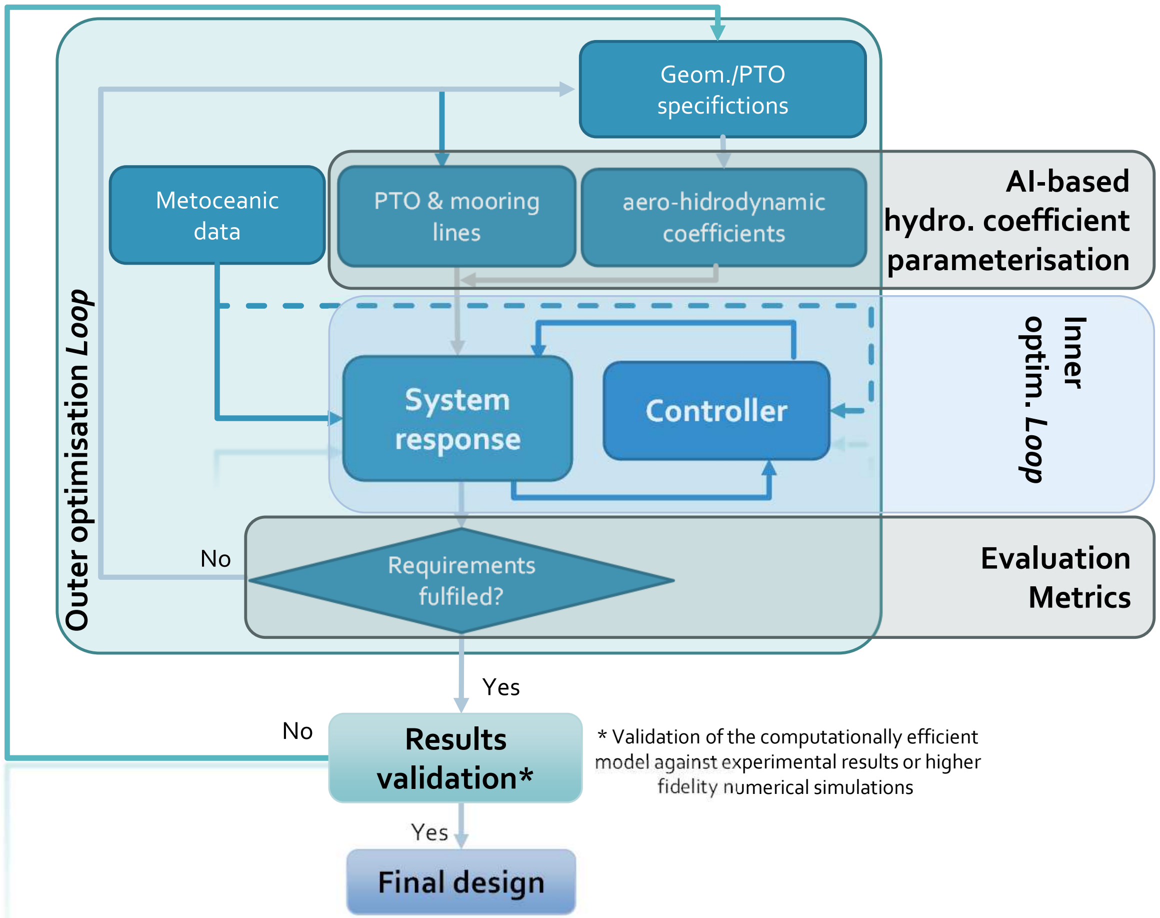
PTO (4)
- Diameters ratio
- Aero. profiles
- # blades
- Rot. speed (ω)

MOORING (3)
- Slack
- # lines
- Diameter

Spar-like floater (4)
- Inside diameters
  - Upper
  - Lower
- Draft
- Thickness/mass

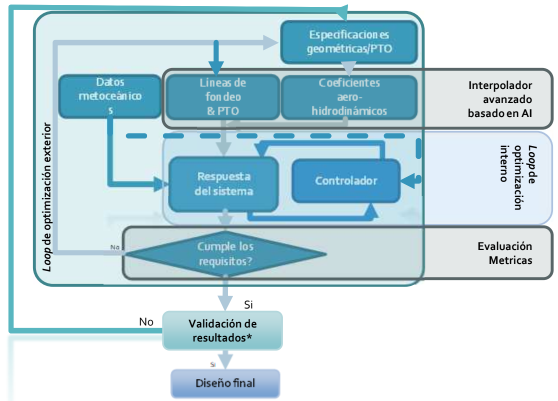
LOADING CONDITIONS
- *Power production mode (operaational region)*
  - Resource characterisations via downscaled climate models
  - Operational region definition via *clustering* techniques

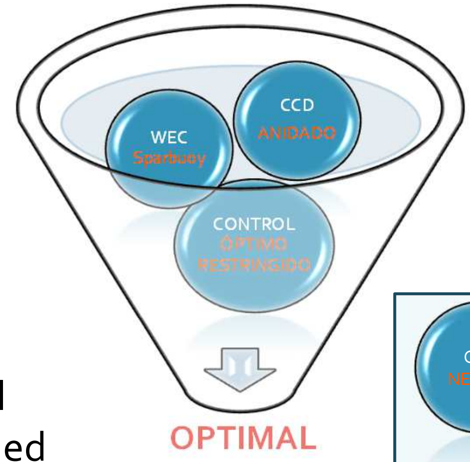
General CCD structure



* Validation of the computationally efficient model against experimental results or higher fidelity numerical simulations

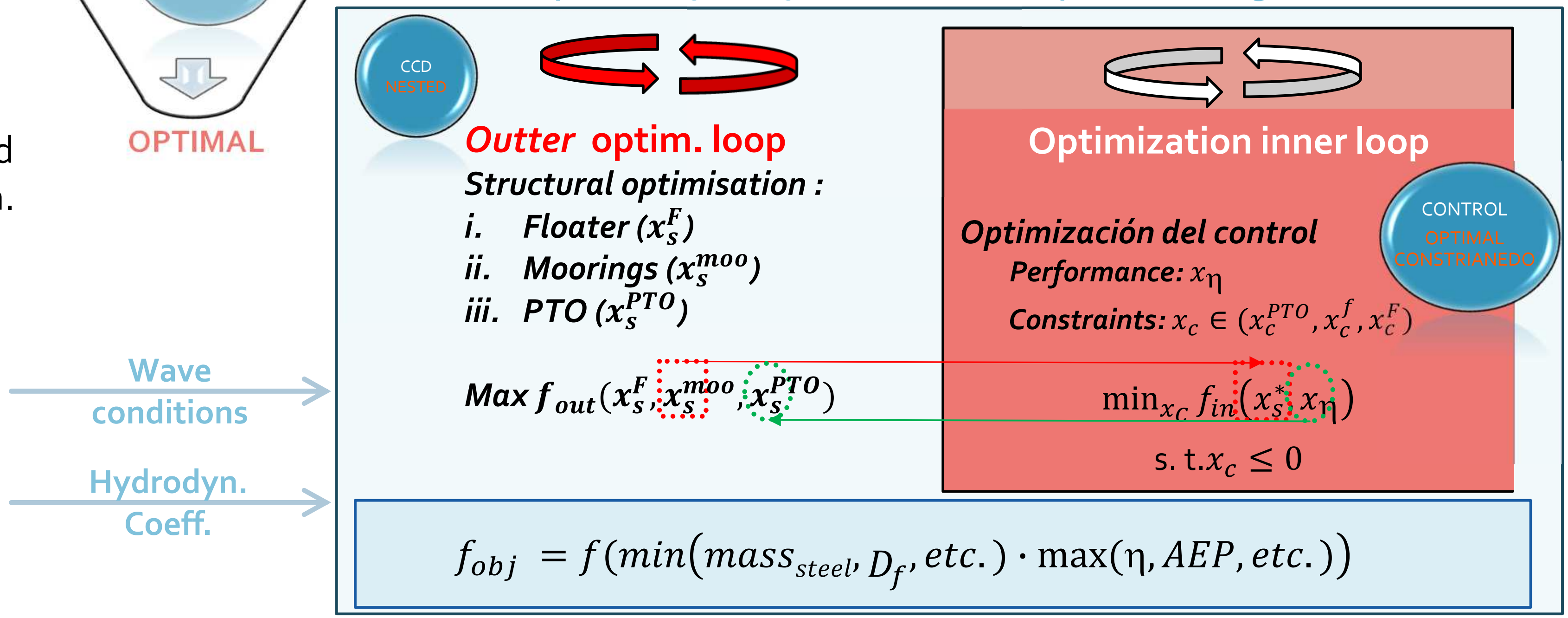
METHODOLOGY





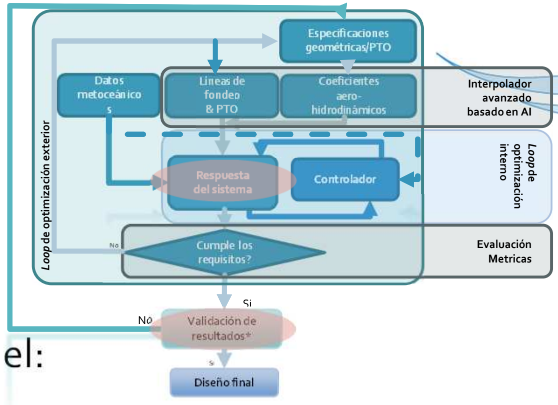
Constrained control optimisation is carried out in the *Inner* optim. Loop for every combination of the *outter* loop

Outer optim. Loop incorporates advanced optimisation algorithms (GA)



Objective metrics (f_{obj}) **t.b.d.**

Advanced modelling



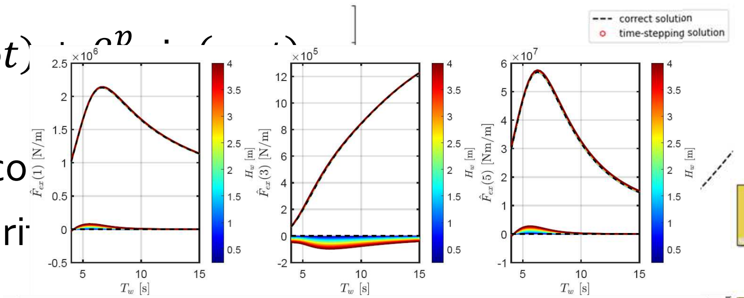
- Math. Model for the controller (*pseudo-espectral)*
  - The spectral model is defined as continuous state-space model:

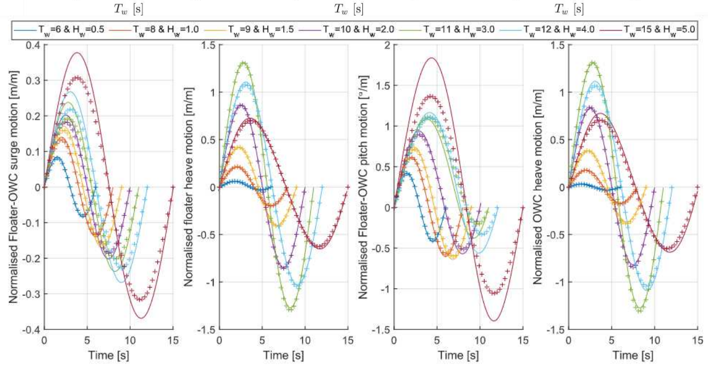
$$\dot{x}(t) = f(x(t), f_{\mathrm{ex}}(t))$$

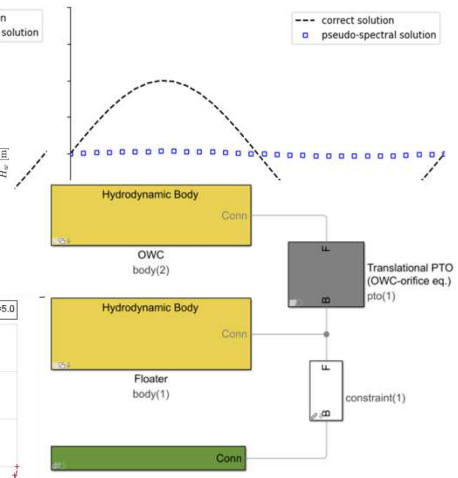
where, $x(t) = [z(t)^T, \dot{z}(t)^T]^T \in \mathbb{R}^{2n_b \times 1}$ y f is the mapping based on harmonic basis functions:

$$\tilde{x}_i(t) = \sum_{p=1}^{N} \alpha_i^p \cos(p\omega t)$$

  - Pseudo-espectral model compatible with co
  - Harmonic-balance model enables non-lineri
- Validación model (non-lineal FK)
  - Instantaneous re-meshing
  - Semi-analytical approximation based on ap
  - Preliminary comparison







Controller design

- Objective function

  Based on energy maximisation

$$E = -\int_0^T P(t)dt = -\int_0^T \dot{z}^\intercal(t) f_{\mathrm{PTO}}(t)dt,$$

$$\max_{f_{\mathrm{PTO}}(t)} \quad -\int_0^T \dot{z}^\intercal(t) f_{\mathrm{PTO}}(t)dt$$

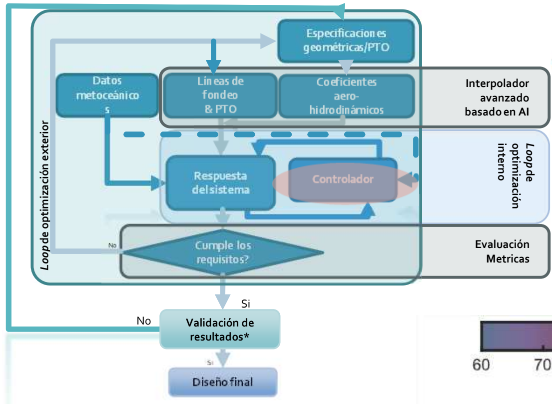
sujeto a

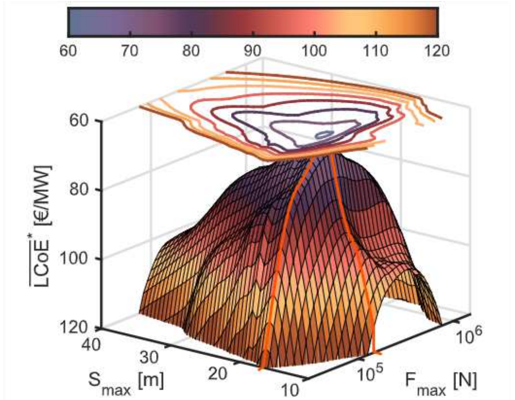
$$\begin{aligned} |z(t)| &\leq Z_{\max}, \\ |f_{\mathrm{PTO}}(t)| &\leq F_{\max}. \end{aligned}$$

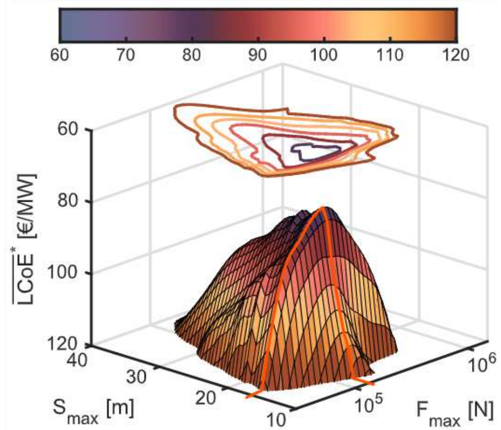
- Cost function defined based on energy/LCOE
- Nonlinearities included in the controller (losses in the PTO)

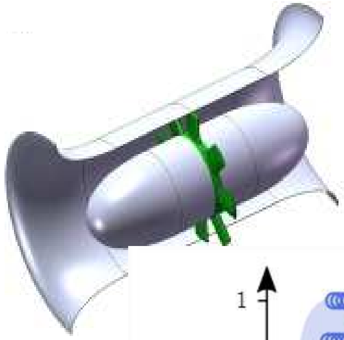
  Losses incoporated in the post-processing (so far)

- On-going work:
  - Coupling the CCD with the PTO optimisation
  - Define displacement/force *constraints* based on realistic floating OWC devices.

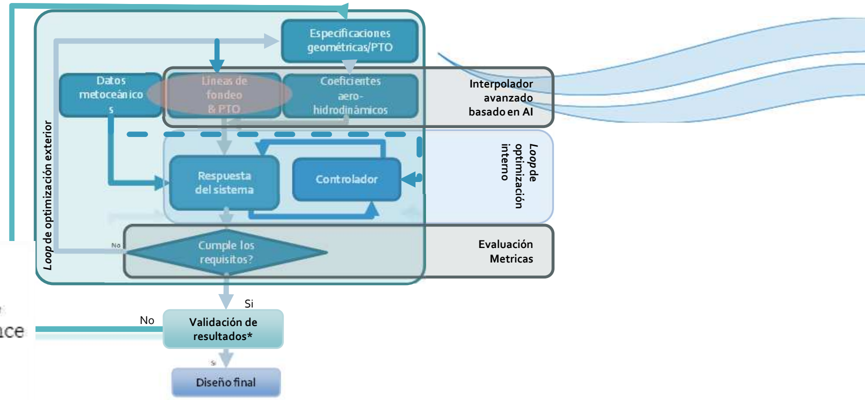


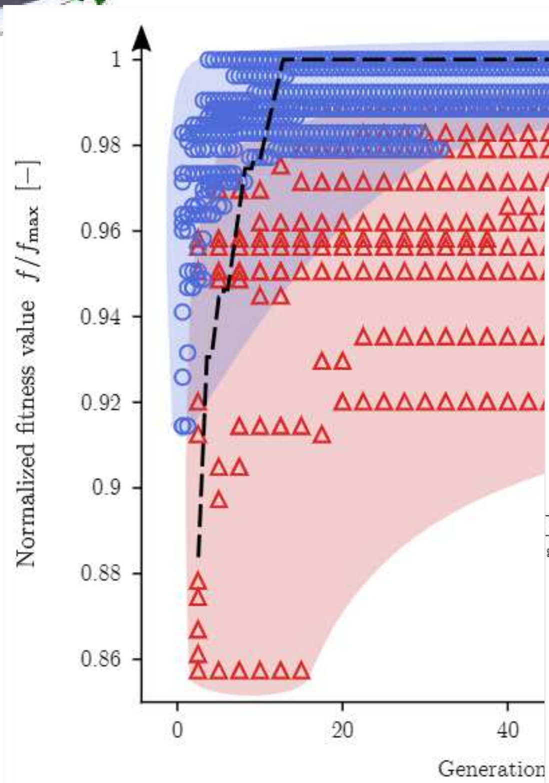


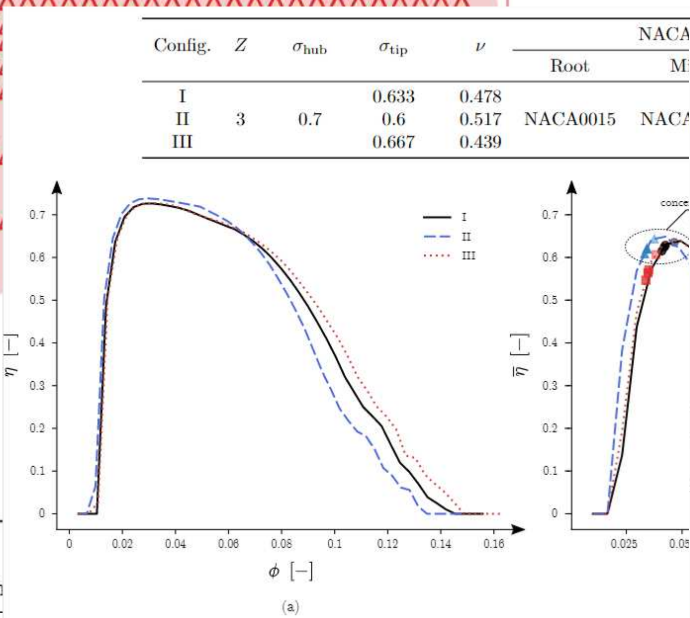


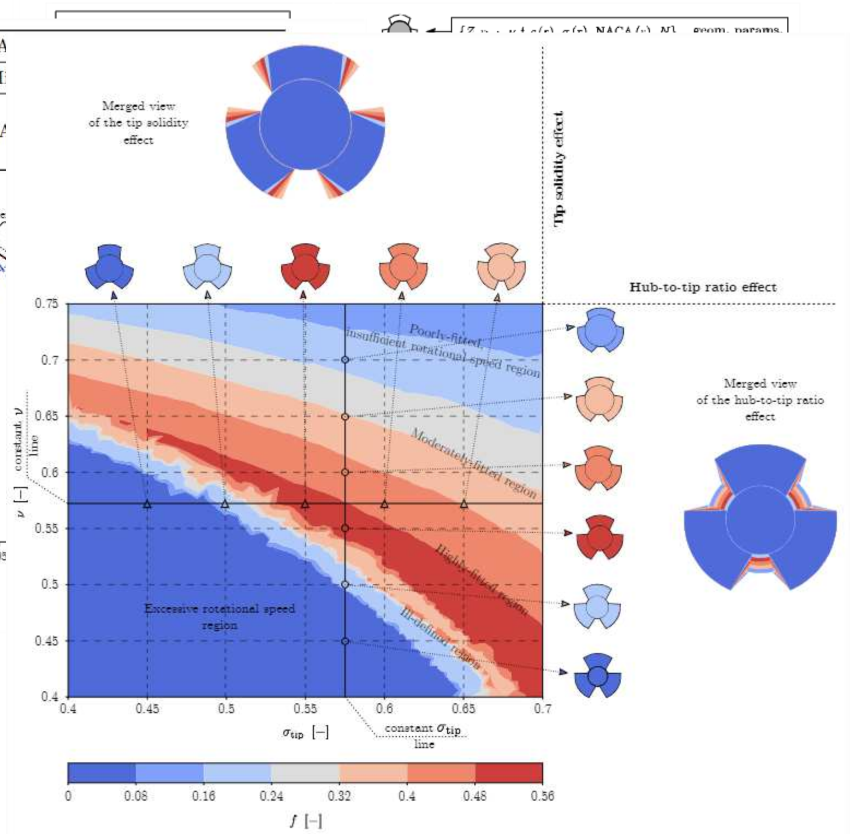


PTO optimisation









Definition of GA parameters (mutation factor, populations size, # genes/generations)

OPTIMIZATION TECHNIQUES

- Adapting metaheuristics to the properties of the problem
  - We train a metaheuristic on a simple problem and apply it to a more complex one.
- Early stopping
  - We stop evaluating unpromising solutions to save time.
- Problems with adjustable precision
  - We can speed up the search process by intelligently adjusting the model precision in real time.
- Co-optimization of morphology and control
  - How to distribute computational resources between morphology and control.

ADVISORY COMMITTE

KONFLOT REMARKS

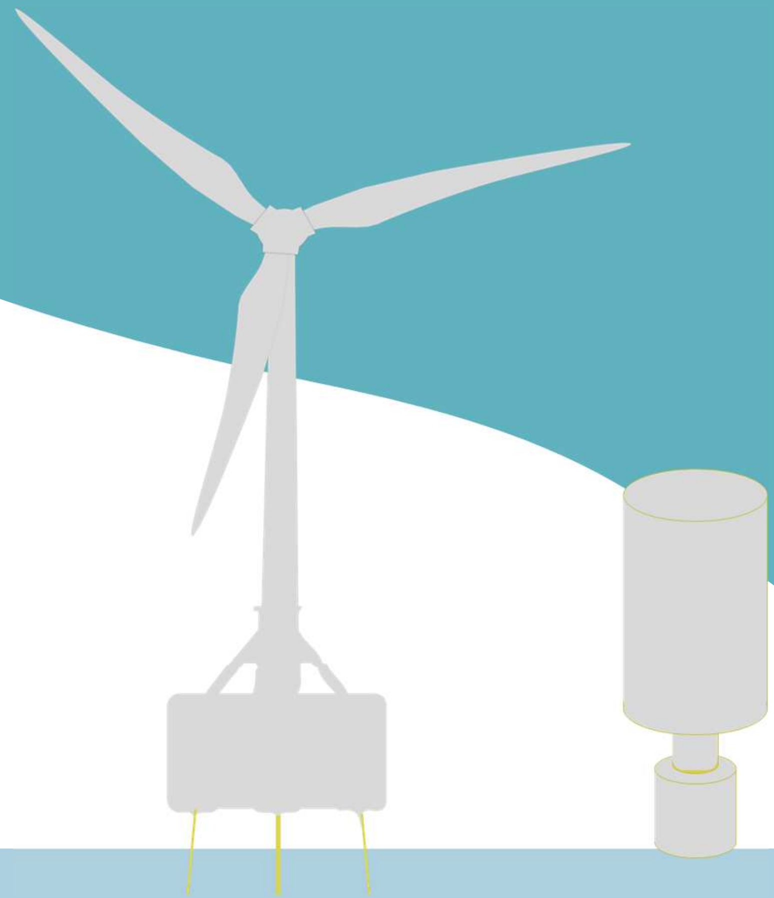
- Teamwork is a must in this project. Partners really believe in what we are doing
- KONFLOT is a starting point of a new design methodology that we think will be the future of ORE. Companies that do not get on board will be out of the race
- It won't be a reality without the active involvement of the industry
- We still have a long way to go. KONFLOT will show that this is the way

BUT

CCD: further requirements

I. **Manufacturability, transportability and O&M issues**

Optimum design may not match with what can be manufactured or transported



CCD: further requirements

II. Include design parameters of other components

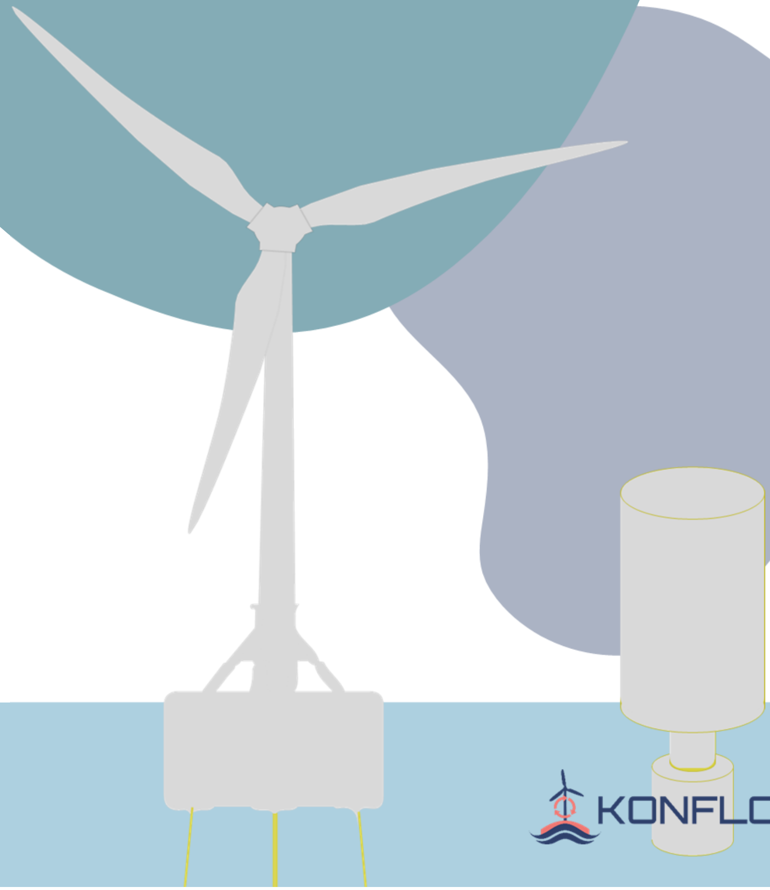
a) **Moorings in WECs**

b) **Dynamic cable**

c) **Anchoring**

d) **Electrical generator**

e) **Advanced parameterization of hydrodynamic coefficients**



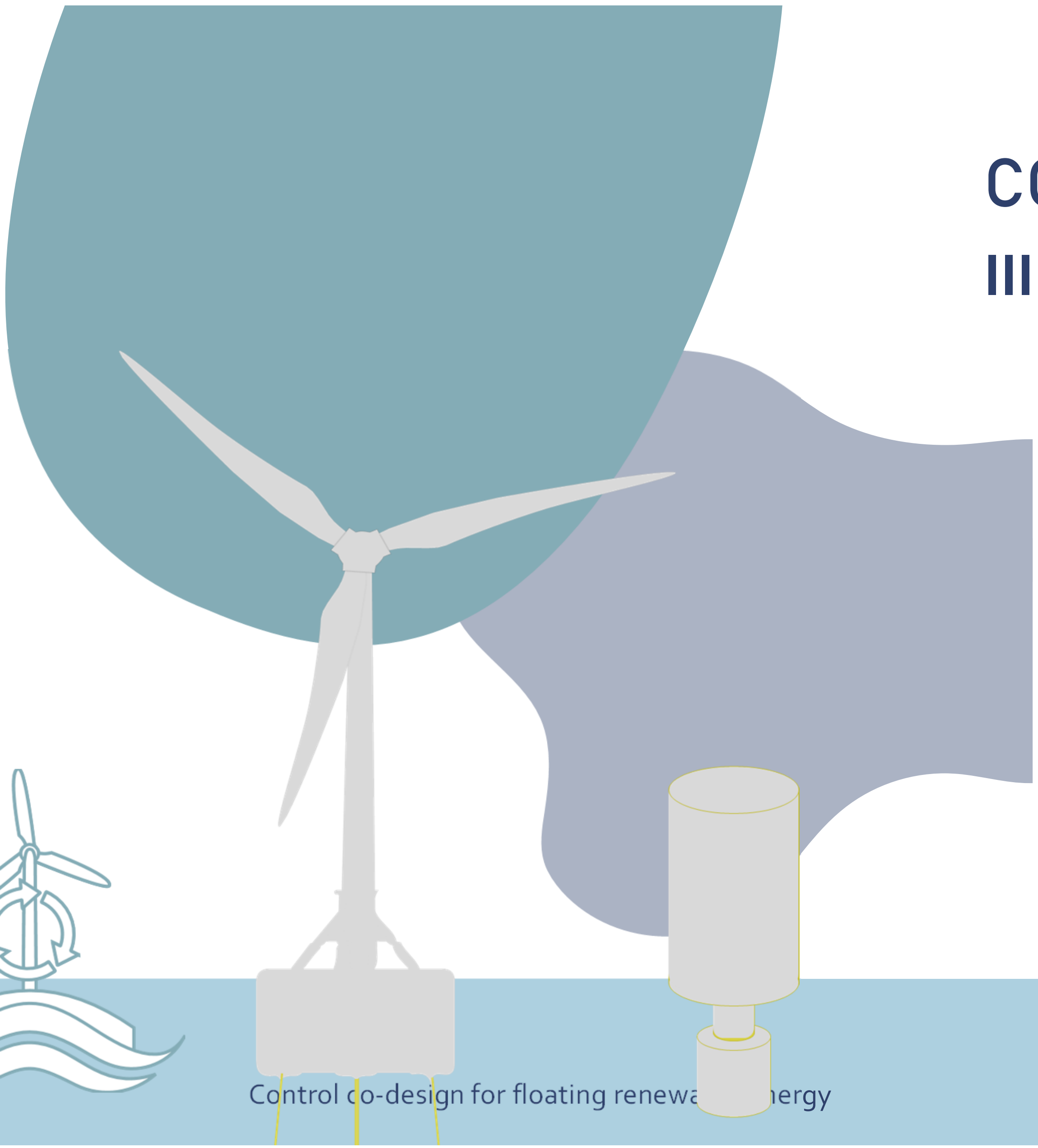
CCD: further requirements

III. Definition of DLCs

a. Real characterization of the resource

b. Definition of operation region

c. Clustering



CCD: further requirements

IV. Multi-device FOWT/WEC

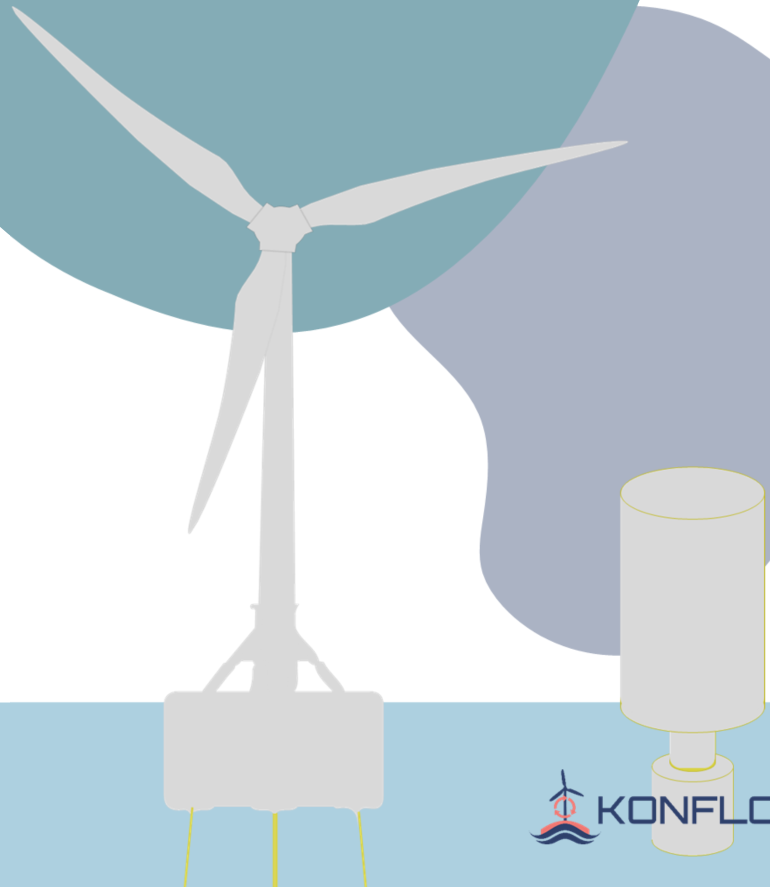
a) Aero-hydrodynamic effects in farms

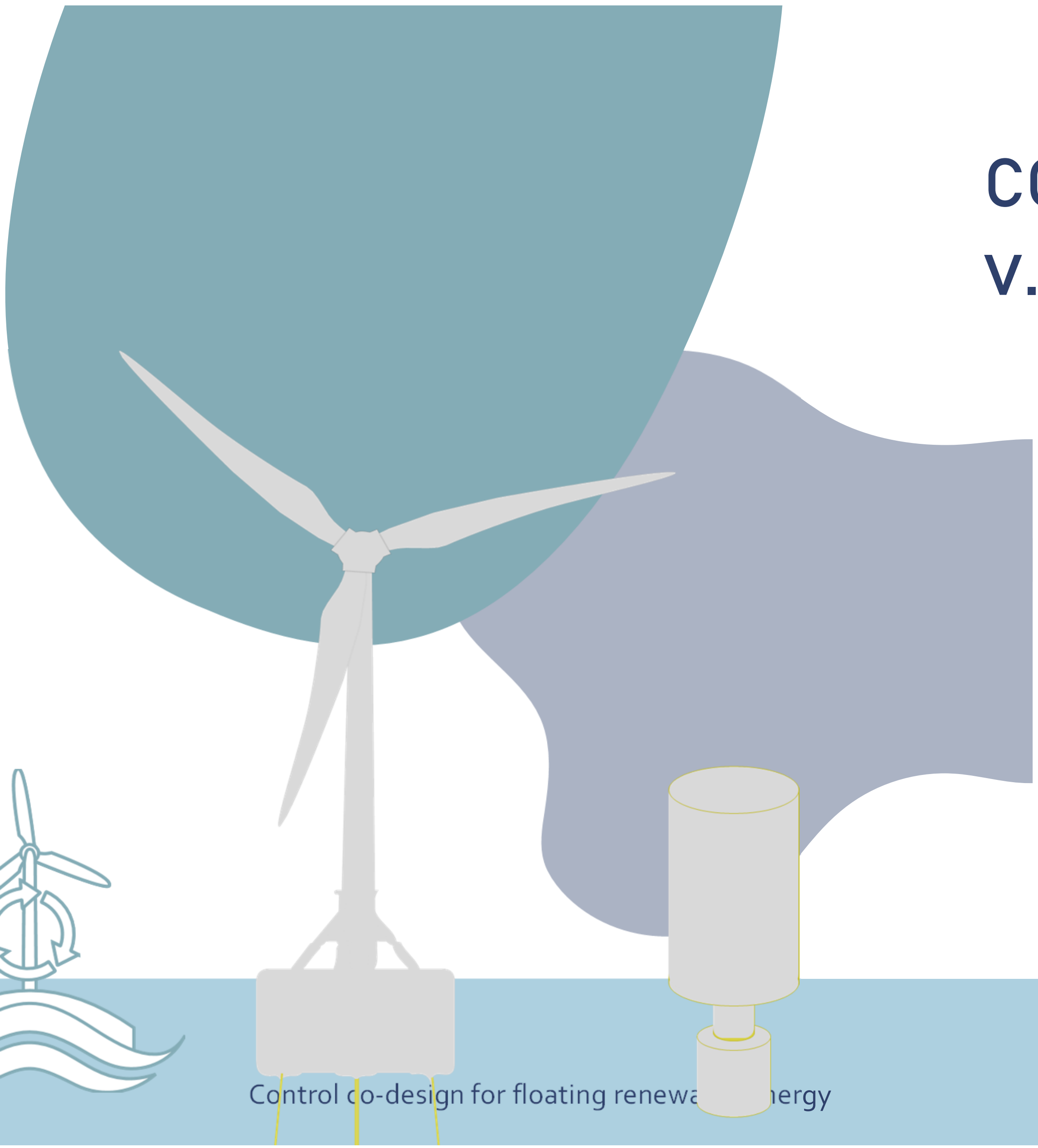
b) Shared moorings lines?

c) Shared dynamic cables?

d) Shared anchors?

e) Shared electrical connection?





CCD: further requirements

V. **Experimental demonstration (proof of concept) of control strategies**

KONFLOT

Codiseño de control de energías renovables flotantes

Eskerrik asko !

¡Gracias!

Eider Robles

664 111 030

eider.robles@tecnalia.com

konflotproject.com

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Cluster Energía BASQUE ENERGY CLUSTER

EUSKO JAURLARITZA GOBIERNO VASCO

EKONOMIAREN GARAPEN, JASANGARRITASUN ETA INGURUMEN SAILA

DEPARTAMENTO DE DESARROLLO ECONÓMICO, SOSTENIBILIDAD Y MEDIO AMBIENTE

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