U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0002049
on
Potential New Program for
Control Co-Design (CCD) of Floating Offshore Wind Turbines (FOWT)

Objective:

The Advanced Research Projects Agency –Energy (ARPA-E) in the U.S. Department of Energy is seeking comments on a **draft** technical section for a possible future program solicitation, which focuses on Control Co-Design of Floating Offshore Wind Turbines. In particular, the **draft** technical section is appended hereto as Attachment A. ARPA-E seeks input from experts in the fields of control and systems engineering, co-design, aerodynamics, hydrodynamics, electrical and mechanical systems, power electronics, electrical generators, structural engineering, naval engineering, modeling, optimization, economics, multi-scale and multi-physics computer algorithms, parallel computing, distributed sensors, intelligent signal processing and actuator networks; as well as developers of offshore wind energy systems and electrical utilities.

All of the information in this RFI and Attachment A is subject to change. **Please carefully review the REQUEST FOR INFORMATION GUIDELINES** below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME. Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.**

Purpose and Need for Information:

The purpose of this RFI is solely to solicit input for ARPA-E consideration, to inform preparation of the draft technical section of a possible future program solicitation prior to its release. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions regarding the draft technical section in Attachment A.

REQUEST FOR INFORMATION GUIDELINES:

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. [Note: Responses to this RFI may be subject to Freedom of Information Act requests.] **Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to the email address ARPA-E-RFI@hq.doe.gov by **5:00 PM Eastern Time on January 8th,** 2019. Emails should conform to the following guidelines:

- Please insert “Comments on Draft CCD FOWT Technical Section”” in the subject line of your email, and include your name, title, organization, type of organization (e.g. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 3 pages in length (12 point font size).

Questions: ARPA-E encourages responses that address any subset of the following questions, and encourages the inclusion of references to important supplementary information.

- The draft Technical Section proposes three fundamental areas (see Section C.4). The first area (C.4.1. New Designs) enumerates a list of examples (cases 1 to 5) where CCD techniques can enable cheaper FOWTs. Please expand these cases and provide additional examples.

- The second area (C.4.2. Computer Tools) details a list of elements (e1 to e10) that are critical for a new generation of computer tools. Please prioritize these elements and provide additional ones.

- The third area (C.4.3. Experiments) describes some key components to collect real data from FOWT. Please provide additional information or critical ideas in this area.

- Section D introduces a new metric space to evaluate the new FOWT designs. The second metric (M2) of this space depends on three factors: a material factor f_t, a manufacturing factor f_m and an installation factor f_i. Table 3 suggests some values for the material factors, f_t. Please analyze these values and provide new ones if necessary. Also, should some additional materials be included? If this is the case, please provide the corresponding material factors.

- Simultaneously, Table 4 suggests some values for the manufacturing and installation factors, f_m and f_i. Please analyze these values and provide new ones if necessary.

- Section D.3 proposes a list of conditions (a to h) to validate each new FOWT design. Please analyze these conditions and provide additional ones if necessary.

- Section C.2 describes three CCD techniques. Please expand these proposed techniques and provide some additional methodologies.

- Section C.1 emphasizes the multidisciplinary nature of the program, with the concurrent control engineering aspects of the control co-design approach. Also, Section E.2 describes the program and project interactions needed to develop a successful CCD approach. Please analyze the aspects (a) to (e) described in the Section (e.g., IP issues, etc.), identify potential hurdles (collaboration challenges, etc.), propose solutions, and suggest how ARPA-E can facilitate these team and multi-team collaborations.

ATTACHMENT A

Draft of Technical Section for

Control Co-Design of Floating Offshore Wind Turbines

B. Envisioned program overview

B.1. Summary

ARPA-E is exploring a new program to develop new technical pathways for the design of economically competitive *Floating Offshore Wind Turbines* (FOWT). The envisioned program would urge the application of *Control Co-Design* (CCD) methodologies that (1) bring together engineering disciplines to work concurrently, as opposed to sequentially, and (2) consider control-engineering principles from the start of the design process. By analyzing the numerous sub-system dynamic interactions that comprise the FOWTs, CCD methodologies can propose control solutions that enable optimal FOWT designs that are not achievable otherwise. Design optimization is defined here as the maximization of the specific power per unit of mass (W/kg) of the FOWT for a given power generation efficiency. The envisioned program would offer a new metric space that quantifies this specific power per unit of mass and the air-to-electron power generation efficiency of the FOWT, and guides the research to navigate across LCOE (*Levelized Cost of Energy*) Pareto-optimal fronts. Projects in this envisioned program would cover three fundamental areas: (1) radically new FOWT designs with significantly lower mass/kW, (2) a new generation of computer tools to control co-design the FOWTs, and (3) real-data from full and lab-scale experiments to validate the FOWT designs and computer tools.

B.2. Motivation

Several comprehensive analyses from NREL[1,2] estimate that the gross offshore wind resource in the U.S. is over 151 quads/yr ("gross potential"). This number is still as large as ~25 quads/yr (or 7,203 TWh/yr in Table 1) even once NREL incorporated losses and conservative assumptions about what would be feasible to recover given technical, legal, regulatory and social inhibiting factors ("technical potential").[3] Fifty-eight percent of this "technical potential" lies in waters deeper than 60 m, accounting for ~14 quads/yr (or 4,178 TWh/yr) for floating offshore wind, which exceeds the entire U.S. annual electricity consumption in 2017 (13 quads/yr or 3,911 TWh/yr).[4]

Table 1. Technical resource potential for floating offshore wind in the U.S. (TWh/yr)[4]

	North Atlantic	South Atlantic	Great Lakes	Gulf Coast	Pacific Coast
Technical Resource Potential	2,081	1,955	492	1,806	869

The viability of offshore wind projects depends on future wholesale electricity prices and capacity

[1] Musial, W., Heimiller, D., Beiter, P., Scott, G., Draxl, C. *2016 Offshore Wind Energy Resource Assessment for the United States*. NREL/TP-5000-66599. National Renewable Energy Laboratory, 2016 (for US mainland and Hawaii).
[2] Doubrawa, P., Scott, G., Musial, W., Kilcher, L., Draxl, C., Lantz, E. *Offshore Wind Energy Resource Assessment for Alaska*. NREL/TP-5000-70553. National Renewable Energy Laboratory, 2017 (for Alaska).
[3] The technical potential was calculated at 3 MW/km^2, and reducing the gross potential using technology exclusion filters that remove areas of wind speeds <7 m/s, water depths >1,000 m, water depths <60 m, competitive-use, environmental constraints and ice constraints.
[4] *National Offshore Wind Strategy: Facilitating the Development of the Offshore Wind Industry in the United States*. U.S. Department of Energy (DOE) and the U.S. Department of the Interior (DOI). September 2016.

market prices within their local electricity market region. These factors can be represented through the *Levelized Avoided Costs of Energy* (LACE), which defines the cost for the grid to generate the electricity that would be displaced by a new FOWT project in the region.

Figure 1 shows the comparison of LCOE and LACE for FOWT over the next few years, as well as the main objectives for the envisioned program. See Section D.2 for more details. When the LCOE falls in the LACE area, then the project has a positive economic potential.

Additionally, the inherent design advantages[5] of FOWTs over bottom-fixed offshore wind turbines create a plausible pathway for them to achieve a cost advantage in the long term. This is shown in DOE's projections, where the LCOE for FOWTs becomes lower than that of bottom-fixed around the year 2027 –see also Fig.1.

State of the art FOWT technology has achieved an average LCOE of approximately $0.15-0.18/kWh, which it is still too high in comparison to the current $0.03-0.05/kWh for land-based wind turbine technologies.[6] High capital expenditures (CAPEX) are the key driver of the LCOE of a FOWT. A significant portion of these CAPEX is the cost of the steel that existing floating platforms incorporate. Floating platforms are designed to be large and heavy in an effort to (a) imitate the onshore wind turbine dynamics, (b) keep the system as stable as possible and (c) maximize system survivability during events such as large sea storms. Internal ARPA-E analysis shows that the cost of steel accounts for between 50% and 70% of the overall CAPEX for existing FOWT designs.[7] Consequently, this envisioned program seeks to design radically new FOWTs that maximize the insufficient specific power per unit of mass (W/kg), while maintaining, or ideally increasing, the turbine generation efficiency. To this end, some technical barriers need to be overcome, including (a) insufficient knowledge of dynamic sub-system interaction, (b) insufficient computer tools for simulation, and (c) insufficient experimental data.

[5] Since they are not fixed systems, FOWTs can be much more easily deployed and retrieved; they are towed out to and from their site for both, installation and major maintenance, and do not required massive deployment vessels.

[6] Stehly, T., Beiter, P., Heimiller, D., Scott, G. (2018). *2017 Cost of Wind Energy Review*. National Renewable Energy Laboratory. Technical Report NREL/TP-6A20-72167 (including cost of substation and electrical lines).

[7] Floating platform mass as percentage of overall system mass is over 70%, based on analysis developed from Myhr, A., Bjerkseter, C., Ågotnes, A., Nygaard, T. (2014). *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*. Renewable Energy, Vol. 66, pp. 714-728.

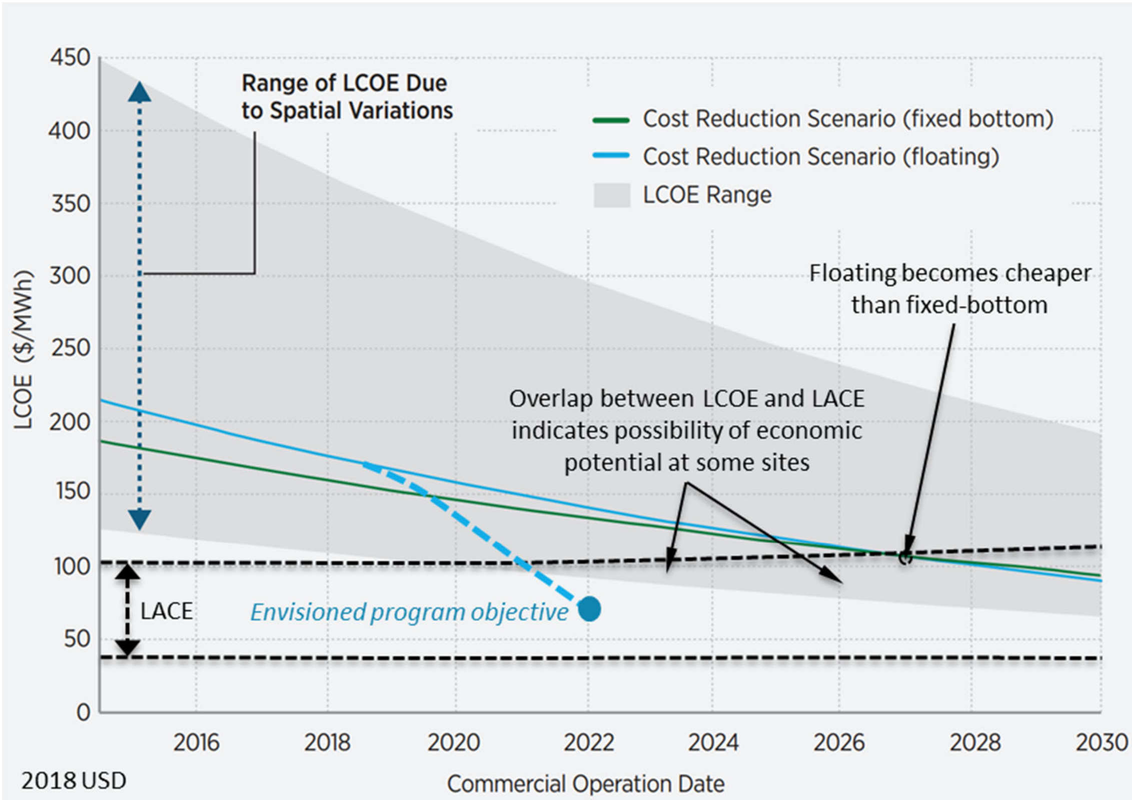

Fig. 1. LCOE and LACE for floating offshore wind. Predictions and objectives.[8]

Insufficient fundamental knowledge. The operational profile of a FOWT system involves coupled nonlinear aero-, hydro-, elastic-, electric-, economic- and servo-dynamics. Industry does not yet have a good understanding of the implications of these coupled dynamics, and therefore these dynamics are not fully incorporated into existing computer tools. Common practice in today's industry is to design the wind turbine and the floating platform separately, by independent teams. The turbine manufacturer usually provides the maximum mechanical torques and platform angles the turbine can support, and the platform manufacturer designs the floating system accordingly, without further coupling considerations. However, it is this complex coupling of multidisciplinary dynamics that makes the FOWT design ARPA-E hard.

Insufficient computer tools. Today's leading computer tools for wind energy system design[9] were created for onshore systems, as opposed to offshore systems, with a more limited set of dynamics to consider. Many of the tools use simplified representations for aerodynamics (Blade Element Momentum Theory), limited description of the hydrodynamics (Morison Equation and first order approximations), and rigid-body equations for the submerged bodies. In addition, they do not have modular capabilities (libraries), do not incorporate control co-design optimization

[8] *National Offshore Wind Strategy: Facilitating the Development of the Offshore Wind Industry in the United States*. U.S. Department of Energy (DOE) and the U.S. Department of the Interior (DOI). September 2016.
[9] Primarily Bladed and various versions of FAST. Bladed, DNV-GL, https://www.dnvgl.com/services/bladed-3775. OpenFAST. (2018). National Renewable Energy Lab, NREL, https://nwtc.nrel.gov/OpenFAST.

techniques, do not integrate electrical and/or economic problems, and are not ready for parallel algorithm implementation.

Insufficient experimental FOWT data. At present, there is almost no experimental data of FOWTs accessible to research and engineering teams other than the 1/8th scale experiment developed by the University of Maine some years ago.[10] The FOWT community needs more experimental data to validate computer tools and improve new designs. This problem has been also largely emphasized in the OC3-OC6 international efforts.[11]

C. Approach

C.1. Control Co-Design definition and examples

Control engineering is the application of mathematics, physics and technology towards autonomous control of physical systems. Control engineers take data about system status and performance, and use microprocessors, various sensors, algorithms, circuits and actuators to improve system conditions and, ultimately, regulate variables automatically. The system can include mechanical and electrical components, chemical and biological characteristics, thermodynamics and fluid dynamics, aero- and hydro-dynamics, network interactions, and more –see Fig.2.

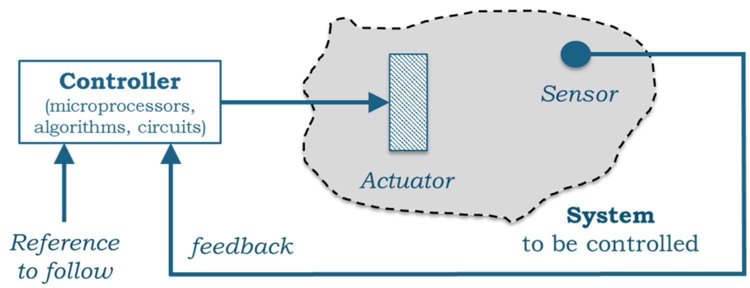

Fig. 2. Control system.

Fundamental to this envisioned program is that control engineering is not limited to finding new ways to regulate existing systems. It can be used to design an entirely new system from the ground up. Instead of the classical design method, where each engineering team (mechanical, electrical, electronics, control, etc.) is an independent step in a sequential process –see Fig.3a, *Control Co-Design* (CCD), also known as *Integrated Control* or just *Co-Design*, brings together various technical disciplines to work concurrently from the start –see Fig.3b.

[10] Dagher, H., Viselli, A., Goupee, A., Kimball, R., Allen, C. (2017). The VolturnUS 1:8 Floating Wind Turbine: Design, Construction, Deployment, Testing, Retrieval, and Inspection of the First Grid-Connected Offshore Wind Turbine in US. United States. Web. doi:10.2172/1375022

[11] International Energy Agency (IEA) Wind Tasks 23 and 30, Offshore Code Comparison Collaboration (OC3/OC4/OC5/OC6 programs) for offshore wind modeling tools.

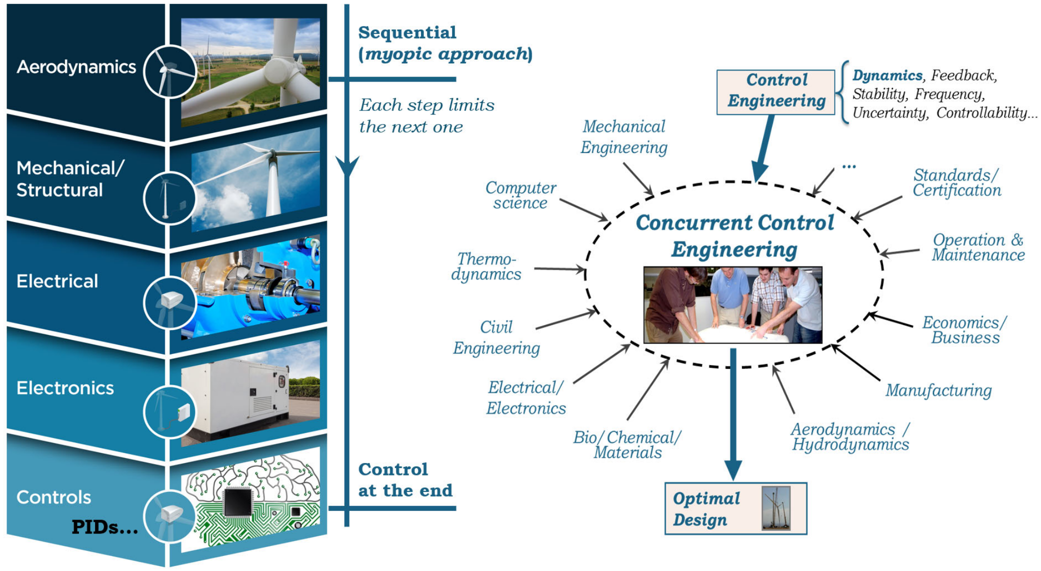

Fig. 3. (a) Classical sequential design process vs. (b) Control Co-Design.

Multidisciplinary systems cannot be fully optimized unless sub-system interactions are considered in the system optimization, which is particularly difficult when system dynamics are involved. CCD techniques consider these dynamic sub-system interactions from the very beginning of the design, and proposes optimal solutions that are not achievable otherwise. This methodology enables a more optimal design—with better system dynamics and controllability, among other advantages – that often results in lower system cost and improved reliability.

Figure 4 presents a CCD example. It is composed of a direct-drive, variable-speed, pitch-controlled 1.65 MW wind turbine. The machine, a type-4 turbine, does not need a gearbox and incorporates a full-power converter to control the aerodynamic efficiency and the grid variables simultaneously and independently. By applying CCD concepts to the pitch control system, the turbine achieved very smooth and robust rotor speed control, reducing also the tower vibration and the corresponding mechanical fatigue of the system (CCD). This second achievement allowed the company to introduce in the market a machine with a tower significantly cheaper (less steel) than the immediate competitor, with also better reliability and robust control characteristics.[12]

Other CCD examples have been proposed over the last few years. Among others, they include smart blades, active control floating systems, new rotor configurations, generators, drive-trains, etc. See Section C.4.1 for additional details.

[12] Garcia-Sanz, M. (2017). *Robust Control Engineering: Practical QFT Solutions*. CRC Press, Boca Raton, Florida. Case Study 2, pages 317-342.

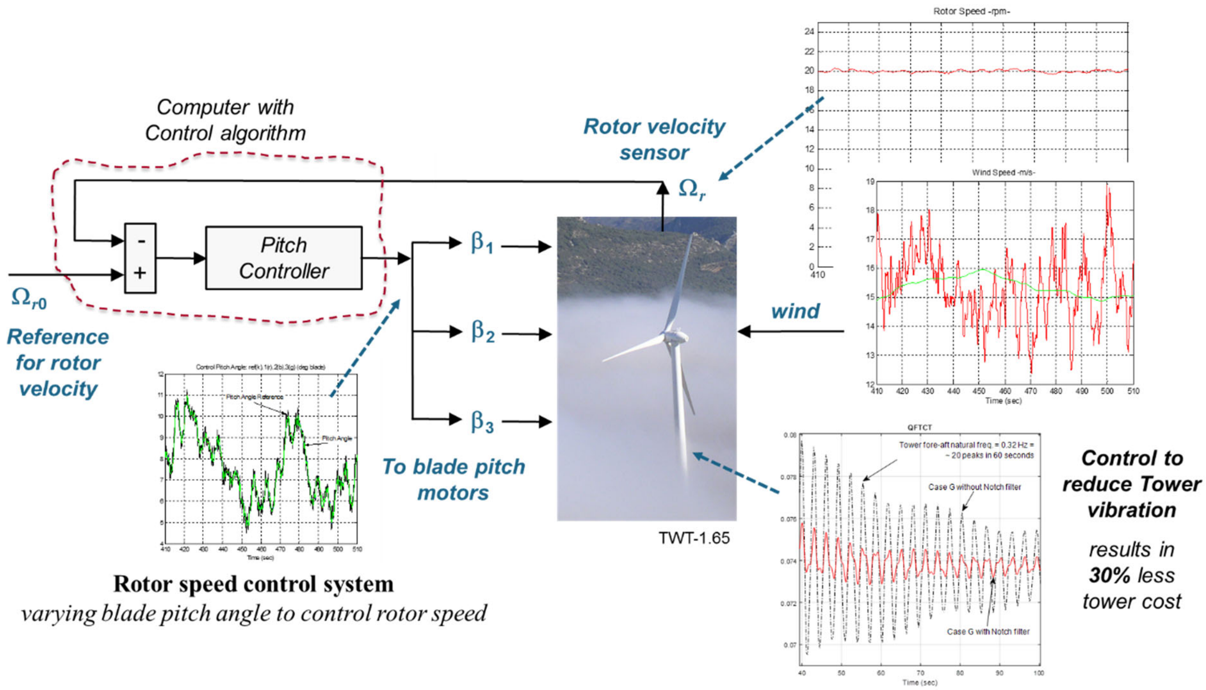

Fig. 4. Example: Control Co-Design of Wind turbine.

C.2. Control Co-Design methodologies

Several CCD techniques to design new optimal FOWT solutions would be considered in this envisioned program, including: (a) control/bio-inspired principles,[13,14] (b) co-optimization techniques[15,16] and (c) co-simulation methods.[17,18]

Control/bio-inspired principles incorporate basic control concepts and bio ideas in the design, including stability principles, resonance mode damping, bandwidth, non-minimum phase characteristics, multi-input multi-output coupling, observability, controllability and others.[19,20]

Co-optimization techniques propose a global optimization exercise where the plant configuration, plant dynamics and controller design are incorporated in a global cost function or

[13] Garcia-Sanz, M. (2017). *Robust Control Engineering: Practical QFT Solutions*. CRC Press, Boca Raton, Florida. Case Study 2, pages 317-342.
[14] Mazumdar, A., Asada, H.H. (2014). *Control-configured design of spheroidal, appendage-free, underwater vehicles*. IEEE Transactions on Robotics, Vol. 30, No. 2, pp. 448-460.
[15] Allison, J.T., Guo, T., Han, Z. (2014). *Co-Design of an Active Suspension Using Simultaneous Dynamic Optimization*. ASME. Journal of Mechanical Design, Vol.136, No.8, pp. 081003.1 – 081003.14.
[16] Kamadan, A., Kiziltas, G., Patoglu, V. (2017). *Co-Design Strategies for Optimal Variable Stiffness Actuation*. IEEE/ASME Transactions on Mechatronics, Vol. 22, No.6, pp. 2768-2779.
[17] Kaslusky,S., Sabatino,D., Zeidner,L. (2007). *ITAPS: A process and toolset to support aircraft level system integration studies*. 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2007-1394, Reno, Nevada.
[18] Reeve, H., Finney, A. (2008). *Probabilistic Analysis for Aircraft Thermal Management System Design and Evaluation*. 46th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2008-148, Reno, Nevada.
[19] Garcia-Sanz, M. (2017). *Robust Control Engineering: Practical QFT Solutions*. CRC Press, Boca Raton, Florida. Case Study 2, pages 317-342.
[20] Mazumdar, A., Asada, H.H. (2014). *Control-configured design of spheroidal, appendage-free, underwater vehicles*. IEEE Transactions on Robotics, Vol. 30, No. 2, pp. 448-460.

in a nested-iterative optimization process.[21,22]

Co-simulation methodologies deal with iterative multi-physics dynamic simulation processes.[23,24]

Figure 5 exemplifies a CCD general methodology that includes a representation of the sub-systems of a floating offshore wind turbine. After applying a set of inputs to the system (wind, waves, grid, etc.), the CCD methodologies analyze the dynamics and sub-system interactions and evaluate the mechanical loads and fatigue, power generation and associated LCOE. Based on these outputs, the methodology looks for potential optimization ideas and re-designs components and control solutions in an iterative process.

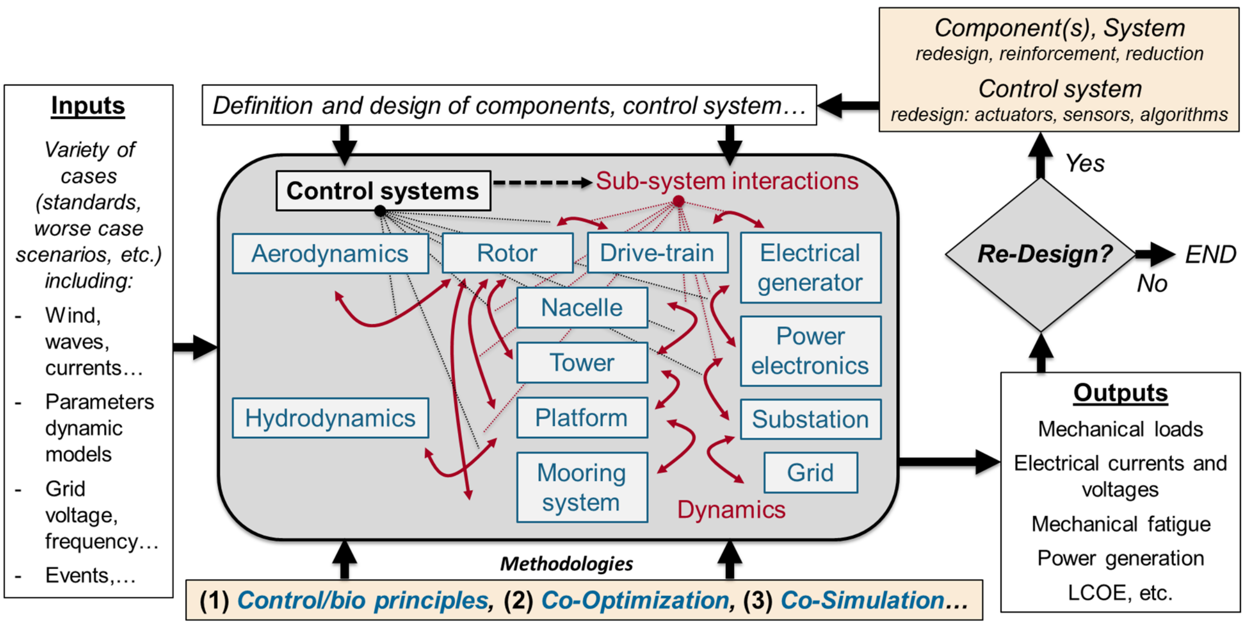

Fig. 5. Control Co-Design diagram.

C.3. Sub-systems Interaction in Floating Offshore Wind Turbines

The highly coupled dynamics involved in the design of FOWTs make this problem an ideal candidate for the CCD approach. Figure 6 shows the main sub-systems of a floating offshore wind turbine: rotor, drive-train, electrical generator, power electronics, substation, nacelle, tower, platform, mooring system, aerodynamics, hydrodynamics, grid and control systems. It also shows the inputs: wind, waves, grid voltage and frequency, etc. The figure emphasizes the multiple sub-system interactions. As a rule, the higher the sub-system interaction, the more effective and needed the control co-design methodology.

[21] Allison, J.T., Guo, T., Han, Z. (2014). *Co-Design of an Active Suspension Using Simultaneous Dynamic Optimization*. ASME. Journal of Mechanical Design, Vol.136, No.8, pp. 081003.1 – 081003.14.

[22] Kamadan, A., Kiziltas, G., Patoglu, V. (2017). *Co-Design Strategies for Optimal Variable Stiffness Actuation*. IEEE/ASME Transactions on Mechatronics, Vol. 22, No.6, pp. 2768-2779.

[23] Kaslusky,S., Sabatino,D., Zeidner,L. (2007). *ITAPS: A process and toolset to support aircraft level system integration studies*. 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2007-1394, Reno, Nevada.

[24] Reeve, H., Finney, A. (2008). *Probabilistic Analysis for Aircraft Thermal Management System Design and Evaluation*. 46th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2008-148, Reno, Nevada.

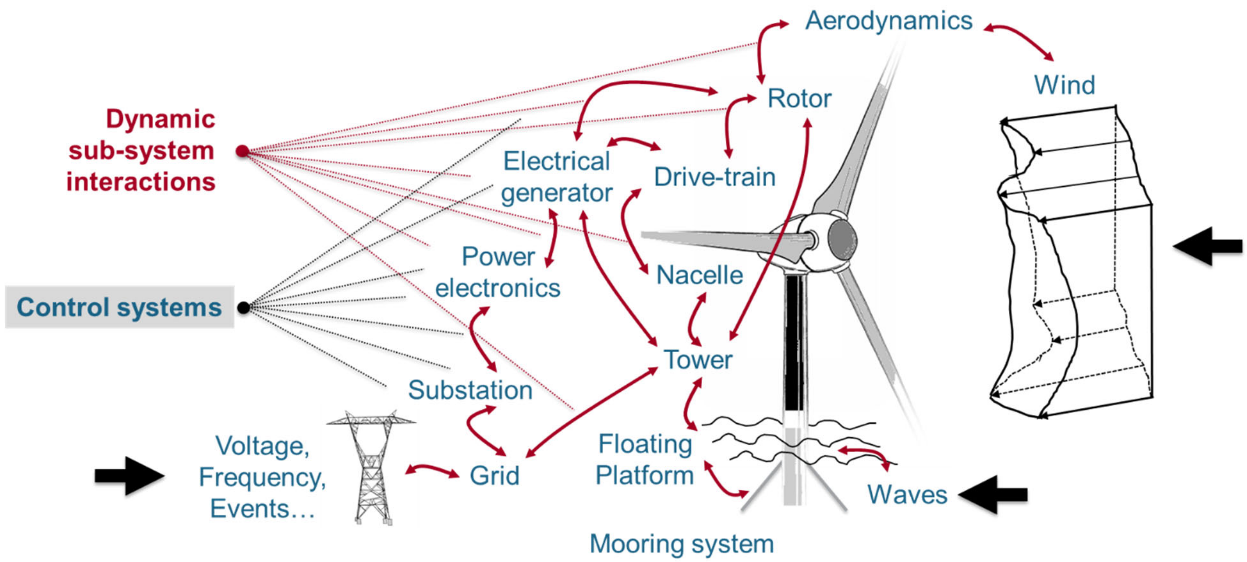

Fig. 6. FOWT sub-system interactions.

Figure 7 presents an example of sub-system interaction in FOWTs. It illustrates the strong interaction among the aerodynamics, the hydrodynamics and the mechanical structure. As the figure shows, the wind moves the rotor of the turbine at a given rotational speed Ω_r. This rotor typically has a very large moment of inertia I_r, especially in multi-megawatt systems. The rotational speed and moment of inertia of the rotor define its angular momentum ($L = I_r \Omega_r$). At the same time, with the turbine working with this angular momentum, a wave hits the system, applying a torque that moves the floating platform, changing the pitch angle of the platform. As a result, a gyroscopic effect will rotate the platform about an axis perpendicular to both the angular momentum and the torque, changing the yaw angle of the floating platform to keep the angular momentum constant (law of conservation of angular momentum).

This aero-hydro-mechanical-control interaction shows the need for a CCD approach to optimize the system. Current industry practices, with independent designs of turbine and platform, cannot achieve an optimal system solution. Moreover, FOWTs have many other important interactions between aerodynamics, hydrodynamics, mechanical structure, mooring system, electrical systems and control systems. The analysis of all these sub-system interactions and the design of innovative control solutions to deal with those interactions in a concurrent control engineering approach (Control Co-Design) are critical to achieve optimal solutions.

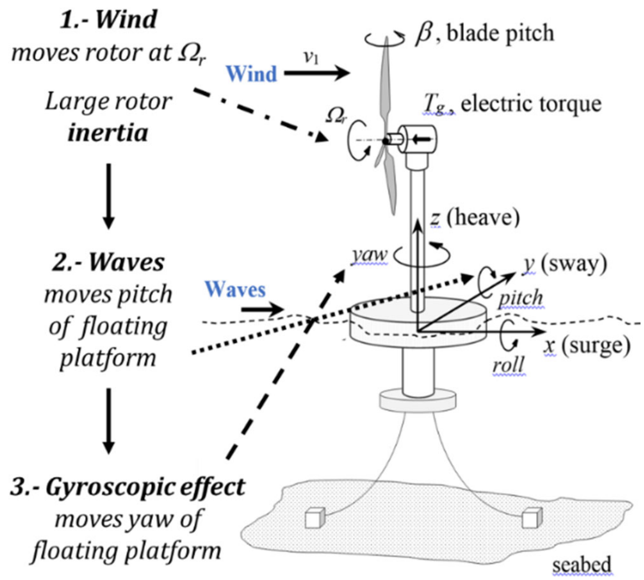

Fig. 7. Example of FOWT sub-system interactions.

C.4. Fundamental areas

The envisioned program would seek to support the development of enabling technologies that establish a new, more promising, technical learning curve for FOWT industry to pursue further. Projects within the proposed program are envisioned in three fundamental areas: (1) radically new FOWT designs, (2) new computer tools to facilitate CCD of the FOWTs, and (3) real-data from full and lab-scale experiments to validate the FOWT designs and computer tools –see Fig.8. Advances in all three of these fundamental areas are vital for this new technical pathway to succeed.

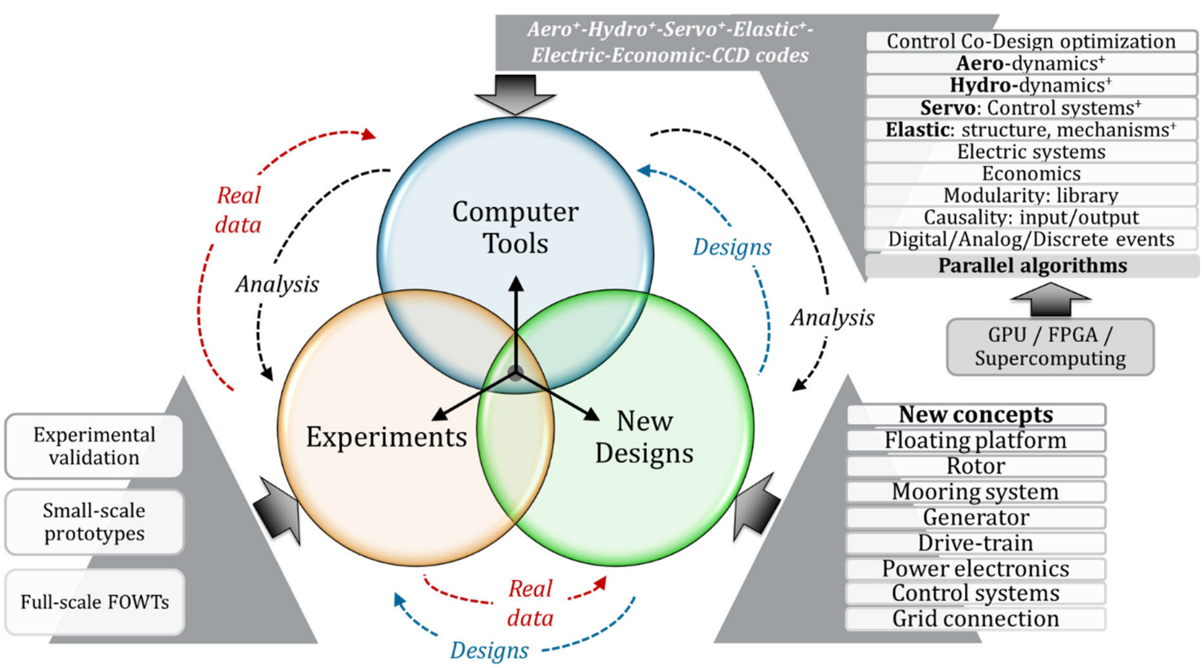

Fig. 8. Envisioned program fundamental areas.

C.4.1. New designs

The first fundamental area deals with radically new FOWT designs. The envisioned program would encourage designs that significantly deviate from the traditional approach of a "stable" or "reinforced" FOWT with an enormous floating platform (conventional spar, semi-submersible or tension leg platforms). In contrast, the new designs are likely to accept and account for some inherent instability and higher compliance, requiring the incorporation of control principles at the core of the design. The underlying hypothesis of the envisioned program is that doing so will shift the burden away from the mechanical system, enabling drastic reductions in mass and associated cost.

Practical FOWT designs have to work in different scenarios, including a normal working operation, surviving under extreme weather conditions, and dealing with transportation, installation and maintenance. These design requirements can be classified in five operational modes: (O1) working mode, (O2) storm mode, (O3) transportation mode, (O4) installation mode, and (O5) maintenance mode. This envisioned program encourages FOWT designs that offer competitive CCD solutions that consider these five operational modes –see Design Load Cases (DLCs), IEC-61400.[25]

Drastically new FOWT designs can be achieved by applying CCD techniques, which typically need innovative control solutions based on new actuators, sensors, algorithms and/or dynamic components. Examples for these new concepts that eventually enable a cheaper FOWT include, but are not limited to:

1. New floating platforms: new designs that balance the main four passive floating principles (i – iv)[26] with semi-active and active structural control systems (v),[27] including:
   (i). *Buoyancy*, or upward acting force, exerted by the fluid, that equals the weight of displaced fluid –Archimedes' principle,
   (ii). *Ballast*, which provides vertical separation of center of gravity (lower) and center of buoyancy (higher),
   (iii). *Mooring*, composed of cables, lines and anchors that holds the system to the seabed,
   (iv). *Viscous damping*, which adds drag and damping to the platform movement,
   (v). *Active control systems,* including innovative actuators, sensors and algorithms to achieve advanced floating dynamics, improving efficiency, survivability and resilience, and reducing costs.
2. New turbine rotors: new configurations and control concepts to improve the aerodynamics and reduce the weight and cost of the FOWT might include:
   (i). Smart blades with innovative plasma/air/flap actuators,[28]

[25] International Electro-technical Commission, IEC 61400-3, Wind turbines – Part 3: Design requirements for offshore wind turbines. https://collections.iec.ch/std/series

[26] Jonkman, J.M., Matha, D. (2011). *Dynamics of offshore floating wind turbines—analysis of three concepts*. Wind Energy, Vol. 14, No. 4, pp. 557-569.

[27] Lackner, M.A., Rotea, M.A. (2011). *Passive structural control of offshore wind turbines*. Wind energy, Vol. 14, No. 3, pp.373-388.

[28] Cooney, J.C., Szlatenyi, C.S., Fine, N.E. (2016). *Development and Demonstration of a Plasma Flow Control System on a 20 KW Wind Turbine*. 54th AIAA Aerospace Sciences Meeting. San Diego, CA, AIAA.

(ii). Individual pitch control systems,[29]
(iii). Vertical-axis rotor configurations,[30]
(iv). Downwind rotors,[31]
(v). Multi-rotor systems,[32]
(vi). Flying turbines,[33,34] etc.

3. New towers, mooring and anchor systems: new configurations and control concepts to reduce the weight and cost of the FOWT might include:
   (i). Flexible towers and systems without tower,
   (ii). Active tension leg platforms,
   (iii). Advanced actuators to damp the tower and/or enhance the control authority of the floating platform, etc.[35]

4. New generators and drive-trains: new configurations and control concepts to reduce the weight and cost of the FOWT might include:
   (i). Reduced-weight electrical generators,[36]
   (ii). Hydraulic drive-trains,
   (iii). Advanced power electronic converters, etc.

5. New materials, manufacturing and installation methods: new control solutions that enable the reduction of weight and cost of the FOWT might include:
   (i). Advanced materials with higher compliance, feasible due to new control solutions,
   (ii). Innovative manufacturing methods for new geometries and mechanical structures,
   (iii). New installation and maintenance systems, like self-deployed controlled systems, etc.

Section D describes a new metric space that defines the targets for the radical new designs sought in this envisioned program.

C.4.2. Computer tools

The radical new FOWT designs presented in the previous section will be based on CCD of today, primarily involving manually intensive incorporation of control principles during design iterations and existing co-simulation tools. Other CCD methodologies such as bio-inspired designs, co-

[29] Wheeler, L., Garcia-Sanz, M. (2017). *Wind turbine collective and individual pitch control using quantitative feedback theory*. ASME 2017 Dynamic Systems and Control Conference, Tysons Corner, Virginia, USA.
[30] Griffith, T., Barone,M., Paquette,J., Owens,B., Bull,D., Simao-Ferriera,C., Goupee,A., Fowler, M. (2018). *Design Studies for Deep-Water Floating Offshore Vertical Axis Wind Turbines*. Sandia Lab. Tech. Rep. SAND2018-7002.
[31] Noyes, C., Qin, C., & Loth, E. (2018). *Pre-aligned downwind rotor for a 13.2 MW wind turbine*. Renewable Energy, 116, 749-754.
[32] Jamieson, P., Branney, M. (2012). *Multi-Rotors; A Solution to 20 MW and Beyond?* Energy Procedia, Vol. 24, pp. 52-59, Elsevier.
[33] Vermillion, C., Grunnagle, T., Lim, R., Kolmanovsky, I. (2014). *Model-Based Plant Design and Hierarchical Control of a Prototype Lighter-Than-Air Wind Energy System, with Experimental Flight Test Results*. IEEE Transactions on Control Systems Technology, Vol.22, No.2, pp. 531 - 542.
[34] Griffith, S., Lynn, P., Hardham, C. (2010). *Wind power generation*. US Patent 7,847,426.
[35] Tang, X., Zuo, L., (2012). *Simultaneous energy harvesting and vibration control of structures with tuned mass dampers. Journal of Intelligent Material Systems and Structures*, Vol. 23, No. 18, pp.2117-2127.
[36] Lee, D., Zheng, L., Jin, A., Min,B.H., Haran, K. (2018). *Optimization method to maximize torque density of high speed slotless PMSM in aerospace applications*. IET Electric Power Applications.

optimization and especially advanced co-simulation will require computer tools that far exceed the capabilities of existing ones for design of FOWTs. Thus, in addition to developing the most optimal new designs via CCD of today, the envisioned program would seek to develop computer tools that enable enhanced CCD for even more optimal new designs. The proposed program would seek to fund the development of enhanced computer tools that include the following elements:

(e1). CCD optimization methodologies,
(e2). New aero-, hydro-, elastic-, servo- mathematical models that incorporate more advanced nonlinear dynamics beyond the OCx programs,[37]
(e3). Libraries of modular functions to allow designers to simulate a large variety of new ideas,
(e4). Tools that run under a standard software environment, like Matlab, Simulink or similar,
(e5). Electrical and economic modules,
(e6). Analog/digital/discrete-event models,
(e7). User-friendly interfaces, easy to use, intuitive and reliable,
(e8). Input/output causality-free codes,[38] instead of pre-defined input/output causality codes,
(e9). IEC-61400 standard inputs, cases and analysis, including the five operational modes introduced in Section C.4.1 and other potential emergency and recovering events,
(e10). Parallel algorithms for GPU and/or FPGA architectures, to speed up the calculations.

Projects to develop these new computer tools would include the most critical elements, like (e1) through (e4), and at least some of the six remaining elements, (e5) to (e10). Overall, developing advanced computer tools for FOWTs will enable the design of next generation FOWT systems.

C.4.3. Experiments

Operational data, from both laboratory prototypes, as well as full scale real-world commercial systems, are urgently needed in this field. Such data will be essential in validating the FOWT designs and computer tools that would be developed in this envisioned program. A publicly available field data repository would facilitate:

- a better understanding of the coupled nonlinear dynamics of FOWTs,
- an experimental validation of the new FOWT designs and computer tools.

To collect such data from full and lab-scale FOWTs, new intelligent real-time systems are needed. These systems include new sensors and network of sensors, advanced data-fusion, observer, learning and classification algorithms, dynamic models and communication devices.

D. Metric Space Definition and Technical Performance Targets

D.1. Metric space definition

The envisioned program would define a new two-dimensional metric space that considers the specific power per unit of mass (W/kg) and the power generation efficiency of the FOWT, and

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[37] International Energy Agency (IEA) Wind Tasks 23 and 30, Offshore Code Comparison Collaboration (OC3/OC4/OC5/OC6 programs) for offshore wind modeling tools.
[38] Like Modelica®. A non-proprietary, object-oriented, equation based language to conveniently model complex physical systems. See https://www.modelica.org

would guide the research to navigate across resulting LCOE Pareto-optimal fronts[39] –see Figs. 9 and 10. This metric space, detailed in this section, is what ARPA-E would use to evaluate new design concepts. All the variables and parameters of this section are expressed in the metric system.

Metric M1

The first metric (M1) represents the ratio between the powers P_{e1} and P_{w1}, both below rated –see eq.(1). P_{w1} is the power of the wind in Watts –see eq.(2). P_{e1} is the electrical power generation at the point of interconnection of the wind turbine to the internal grid of the wind farm (output of the wind turbine) in Watts –see eq.(3). Both powers, P_{e1} and P_{w1}, are calculated at the same wind speed, V_1 = 8 m/s. This speed V_1 is below rated, and is selected so that the maximum power point tracking (MPPT) control strategy is keeping the aerodynamic power coefficient C_p at the maximum value C_{pmax}, and with a constant pitch angle β –see eq.(4). The efficiency μ includes the generator losses L_g, drive-train losses L_{dt} (gearbox and power electronics), wake effect losses L_w due to the aerodynamic interaction of turbines in the farm, electrical losses L_e (substation and electrical lines, intra-wind-farm and farm-to-shore), wind turbine availability A_v and other losses L_o –see eq.(5). In summary, the main equations for M1 are:

$$M_1 = \left.\frac{P_{e1}}{P_{w1}}\right|_{at\ V_1} = C_p\ \mu \quad (1)$$

$$P_{w1} = \frac{1}{2}\ \rho\ A\ V_1^3 \quad (2)$$

$$P_{e1} = \frac{1}{2}\ \rho\ A\ C_p\ \mu\ V_1^3 \quad (3)$$

$$C_p = C_{pmax} \quad (4)$$

$$\mu = \left(1 - L_g\right)\left(1 - L_{dt}\right)\left(1 - L_w\right)\left(1 - L_e\right)\left(1 - L_o\right) A_v \quad (5)$$

where:

→ ρ = 1.225 kg/m^3 is the density of the air,
→ $A = \pi R^2$ is the swept area of the rotor in m^2,
→ V_1 = 8 m/s is the selected undisturbed upstream wind velocity, below rated,
→ μ is the efficiency of the system, including (all in per unit):

- L_g: generator losses,
- L_{dt}: drive-train (gearbox and power electronics) losses,
- L_w: wake effect losses due to the aerodynamic interaction of turbines in the farm,
- L_e: electrical losses (substation and electrical lines, intra-wind-farm and farm-to-shore),
- L_o: other losses,
- A_v: wind turbine availability.

Physically speaking, M1 represents the power generation efficiency of the wind turbine ($C_p\ \mu$), from the upstream-undisturbed wind to the electrical output of the turbine.

[39] Garcia-Sanz, M. (2019). A metric space with LCOE Pareto-optimal fronts for research guidance in wind energy. Submitted to Wind Energy, Wiley.

Also, M1 is proportional to the electrical power per unit area of the rotor (W/m^2) at the selected below rated wind speed V_1: i.e. M1 = $k\ (P_{e1}\,/\,A)$, with $k = 1/(0.5\ \rho\ V_1^3)$.

Metric M2

The second metric (M2) represents the ratio between the arithmetic mean of the powers P_{er} and P_{w1}, and the equivalent mass M_{eq} of the FOWT –see eq.(6). P_{er} is the rated electrical power at the output of the turbine, and P_{w1} the power of the wind at V_1 –see eq.(2), both in Watts. M_{eq} is the equivalent mass of steel (steel of reference type) of the FOWT in kilograms –see eq.(7).

$$M_2 = \frac{\frac{(P_{er}+P_{w1})}{2}}{M_{eq}} \tag{6}$$

$$M_{eq} = \sum_{j=1}^{8} m_j, \tag{7a}$$

$$\text{where } m_j = f_{tj}\,(1 + f_{mj} + f_{ij})\,m_{cj}\text{, and } \begin{cases} f_t = \text{material factor} \\ f_m = \text{manufacturing factor} \\ f_i = \text{installation factor} \\ m_c = \text{mass of component (kg)} \end{cases} \tag{7b}$$

The equivalent mass M_{eq} is composed of eight elements m_j, j = 1 to 8, which represent each major component of the FOWT from the air to the electrical output: m_1 = rotor, m_2 = hub, m_3 = nacelle, m_4 = tower, m_5 = floating platform, m_6 = mooring system, m_7 = anchor system and m_8 = electrical system, all in kg. Each element m_j denotes the equivalent mass of the component j as made of steel of reference. In other words, by multiplying the equivalent mass (kg) of each component m_j by the cost of the steel of reference ($/kg), we obtain the cost of each component j ($), regardless of the type of material it is made of, and including all the manufacturing and installation costs. The *steel of reference* for this envisioned program is defined as a high corrosion resistant austenitic stainless steel.

The actual mass of each component, made of its original material, is represented by m_c and is expressed in kg. The material factor f_t is non-dimensional, and represents the ratio between the cost of one kilogram of the original material ($/kg) divided by the cost of one kilogram of steel of reference ($/kg). The manufacturing factor f_m is also non-dimensional, and represents the ratio between the cost per kilogram of the manufacturing of the component ($/kg) divided by the cost of one kilogram of steel of reference ($/kg). Finally, the installation factor f_i, also non-dimensional, represents the ratio between the cost per kilogram of the installation of the component ($/kg) divided by the cost of one kilogram of steel of reference ($/kg).

Excluding the financial costs, the equivalent mass M_{eq} can also be calculated by dividing the CapEx ($) by the cost of one kilogram of steel of reference ($/kg). Values are shown in Tables 2 to 4.

LCOE Pareto-optimal fronts

As it is well known, LCOE is a function of the capital expenditures CapEx ($), the fixed charge rate FCR (1/year), the operation and maintenance expenditures OpEx ($/year), and the annual energy production AEP (kWh) –see eq.(8).

$$LCOE = \frac{FCR\ CapEx + OpEx}{AEP} \tag{8}$$

M1 affects the annual energy production. As M1 increases, AEP also increases, and LCOE decreases ($M_1 \uparrow \rightarrow AEP \uparrow \rightarrow LCOE \downarrow$). At the same time, M2 affects CapEx. As M2 increases, CapEx decreases, and LCOE decreases ($M_2 \uparrow \rightarrow CapEx \downarrow \rightarrow LCOE \downarrow$).

Putting the two metrics M1 and M2 together in a two-dimension orthogonal space, we can identify LCOE Pareto-optimal fronts for each case of study. Figure 9 shows the new metric space and the LCOE Pareto fronts based on three systems of the most recent NREL market study,[40] including floating offshore wind turbines (circle), bottom-fixed offshore wind turbines (diamond), and onshore wind turbines (right-pointing triangle). The calculations exclude the substation costs and the electrical line costs (intra-wind-farm and farm-to-shore lines), or m_8 = 0.

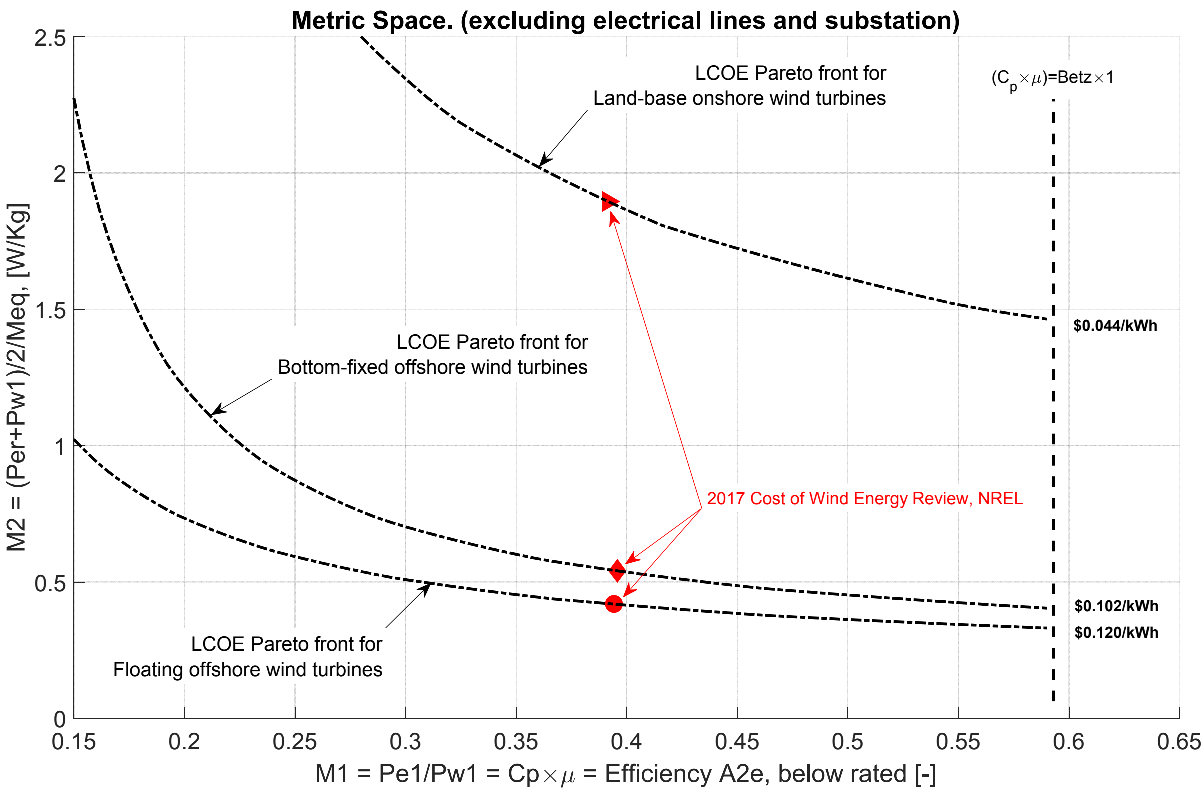

Fig. 9. Metric space definition.

<u>Example 1.</u> (Original case)

The case corresponding to the circle in Fig.9 is presented here as an illustrative example to understand how to calculate the new metrics. This case is the average floating offshore wind turbine presented in the NREL 2017 Cost of Wind Energy Review.

- *<u>Metric M1</u>*:

  The FOWT of this example has the following aerodynamic coefficient and losses: C_{pmax} = 0.47, L_g = 0.04; L_{dt} = 0.02; L_w = 0.05; L_e = 0; L_o = 0 and A_v = 0.9387. Applying eqs.(4) and (5) gives C_p

[40] Stehly, T., Beiter, P., Heimiller, D., Scott, G. (2018). *2017 Cost of Wind Energy Review*. National Renewable Energy Laboratory. Technical Report NREL/TP-6A20-72167.

= 0.47 and μ = 0.839, which in eq.(1) gives M1 = $C_p\,\mu$ = 0.3943.

- *Metric M2*:

In addition, the turbine has a rated electric power P_{er} = 5.64e6 W, a rotor radius = 140/2 m, a wind power at V_1 of P_{w1} = 4.8275e6 W, and the masses and factors shown in Table 2.

Table 2. Information for M_{eq}, Example 1

j	*Component*	m_j	f_{tj}	f_{mj}	f_{ij}	m_{cj}
1	Rotor (blades)	1.2094e6	4	3	0.5	6.7189e4
2	Hub (with pitch systems)	1.5150e5	1	0.6	0.5	7.2144e4
3	Nacelle (generator, drive-train, yaw…)	1.3742e6	1	3	0.5	3.0537e5
4	Tower	1.0596e6	1	0.9	0.5	4.4152e5
5	Floating platform	8.5887e6	1	1.2	0.5	3.1810e6
6	Mooring system	7.7870e4	1	0.1	0.1	6.4892e4
7	Anchor system	3.1148e4	0.3	0.1	0.1	8.6522e4
8	Electrical system (substation, lines)	0 (excluded)	1.5	0.16	0.1	1.7345e6

Applying eqs.(7a,b) results in M_{eq} = 12.4924e6, which with the powers P_{er} and P_{w1} in eq.(6) gives: M2 = 0.4190 W/kg.

Note: As Table 2 shows, the principal components in the total equivalent mass M_{eq} are the floating platform (m_5 ≈ 70%), nacelle (m_3 ≈ 10%), rotor (m_1 ≈ 10%) and tower (m_4 ≈ 10%). Figure 10 compares the effect of each component. As this envisioned program attempts to increase the specific power per unit of mass, new designs that reduce significantly the mass of the floating platform, and some of the tower, rotor and nacelle are encouraged.

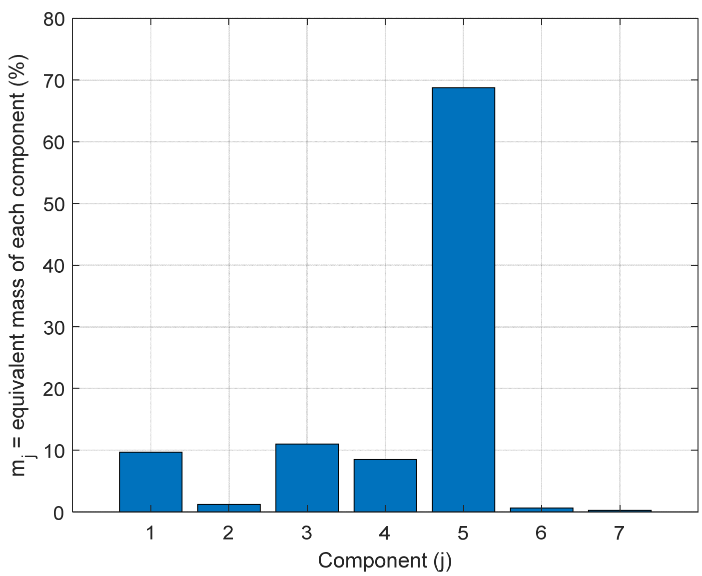

Fig. 10. Equivalent mass m_j of each component j of Table 2, in percentage.

- *Associated LCOE calculation* (not needed for M1, M2):

A pair of metrics (M1,M2) can give different LCOE results. The LCOE depends on other additional parameters related to the site and economic factors. As an example, by choosing the parameters given below, the associated CapEx and LCOE are: CapEx = 4430 $/kWe, LCOE = $0.1204/kWh (the substation and the electrical line costs are not included)[41].

Parameters

→ Wind: Average speed V_{ave} = 8.97 m/s, k = 2.1 (Weibull), $V_{cut\text{-}in}$ = 3 m/s, $V_{cut\text{-}out}$ = 25 m/s
→ Sea: North Atlantic
→ Annual energy production, AEP = 3732 MWh/MW/yr (wind shear exponent of 0.1 applied)
→ Fixed charge rate, FCR = 8.2%
→ OpEx = 86 $/kWe/yr
→ Water depth = 100 m
→ Distance from shore = 30 km
→ Number of turbines in wind farm = 107
→ Project number of years = 20 years
→ Cost of Steel of reference = $2/Kg (high corrosion resistant austenitic stainless steel)

D.2. Envisioned program performance objectives

The new FOWT designs proposed for the envisioned program have to be above the LCOE Pareto-optimal front shown in Fig.11. This envisioned program likely objective is expressed in terms of the two metrics M1 and M2, and for the polynomial and inequalities defined by the following expressions:

$$M_2 \geq a_{10}\, M_1^{10} + a_9\, M_1^{9} + \cdots + a_2\, M_1^{2} + a_1 M_1 + a_0 \qquad (9)$$

with:

$a_{10} = 3745545.13$, $a_9 = -14631449.98$, $a_8 = 25430326.23$, $a_7 = -25900515.61$,
$a_6 = 17124177.25$, $a_5 = -7684134.56$, $a_4 = 2372586.78$, $a_3 = -498652.83$,
$a_2 = 68500.05$, $a_1 = -5590.87$, $a_0 = 209.99$

and: $0.15 \leq M_1 \leq 0.593$

These expressions have been calculated for approximately a 50% of the LCOE of Example 1 above, and for the same assumptions and parameters (site and economic factors) of that example.

Example 2. (Improved case)

To illustrate the envisioned program likely performance objectives, an improved design based on the conventional average floating offshore wind turbine case introduced in Example 1 (Section D.1) is presented here. The original case is at M1 = 0.3943, M2 = 0.4190 W/kg.

The improved design, which meets the envisioned program objectives, is at M1 = 0.3943, M2 = 1.0426 W/kg –see small blue square in Fig.11. This can be achieved by keeping the same efficiency M1 of the original case, reducing the mass of the floating platform (0.25 × m_5), rotor (0.75 × m_1) and tower (0.75 × m_4), increasing the rated electric power to P_{er} = 6.0e6 W, and simultaneously increasing the rotor radius to 85 m, which gives a wind power below rated of P_{w1} = 7.1181e6 W.

[41] LCOE is $0.146/kWh if the substation and the electrical line costs, with intra-wind-farm and farm-to-shore lines, are included, or m_8 = 3.2783e6 ≠ 0. This gives CapEx = 5605 $/kWe instead of 4430 $/kWe.

Example 3. (Improved case)

A second improved case, based on an unconventional design, is also shown in Fig.11. The design is an airborne-type FOWT, with tethers instead of a tower, a small floating platform and a lightweight rotor. In this case, the losses are the same as in Example 1, but with a lower aerodynamic coefficient C_{pmax} = 0.34. The selected rated power is P_{er} = 3.0e6 W and the effective rotor radius of the flying system 60 m, which gives a wind power below rated of P_{w1} = 3.5467e6 W at V_1 = 8 m/s. For simplicity, the equivalent masses m_2, m_3, m_6 and m_7 are calculated from Example 1 (Table 2), as a reduced case for less rated power and diameter. At the same time, the equivalent masses of the floating platform, tower and rotor are significantly lighter in comparison to the reduced case calculated from Example 1 (m_5, m_4, m_1), being: (0.05 × m_5), (0.14 × m_4) and (0.10 × m_1). This improved case also meets the envisioned program objectives, with M1 = 0.2853 and M2 = 1.4747 W/kg –see small green square in Fig.11.

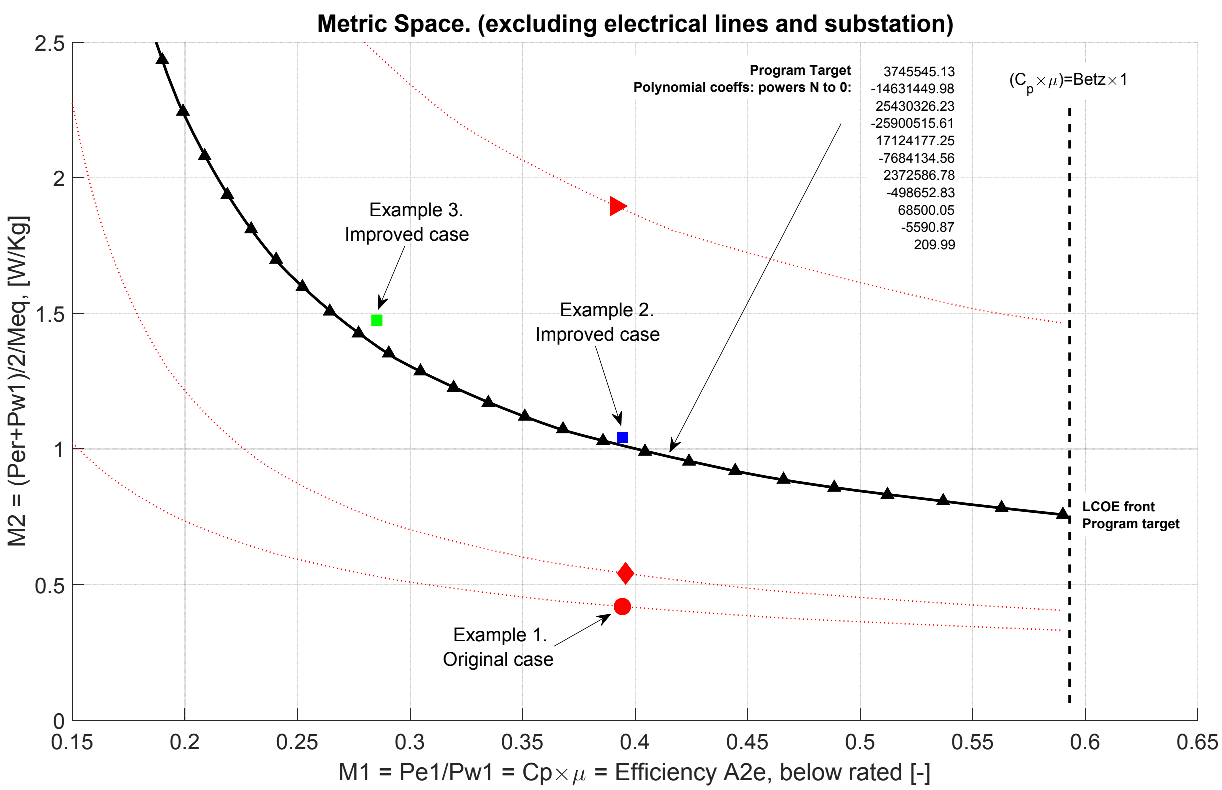

Fig. 11. Envisioned program performance target. FOWT new designs have to be above the LCOE Pareto-front represented by the solid line with triangles.

D.3. Design validation

The calculation of the equivalent mass M_{eq} needs three factors for each component: the material factor f_t, the manufacturing factor f_m, and the installation factor f_i. Table 3 shows the material factors f_t that would be used in the calculations of this envisioned program by default. If the new design of the FOWT needs another material that is not shown in Table 3, a new material factor f_t for that new material must be proposed and justified.

Table 3. Material factors (raw materials)[42]

f_t = cost original material ($/kg) / cost steel of reference ($/kg)

Material	Material factor f_t
Aluminum alloys	4.0
Brass (70Cu30Zn, annealed)	1.1
CFRP Laminate (carbon fiber reinforce polymer)	80.0
Copper alloys	1.5
GFRP Laminate (glass-fiber reinforced plastic or fiberglass)	4.0
Lead alloys	0.6
Nickel alloys	3.0
Polyester and Epoxy Resins	5.5
Reinforced concrete	0.3
Titanium alloys	22.5
Steel of reference, to calculate f_t factors	**1.0**

Table 4. Manufacturing and installation factors[43]

f_m = cost manufacturing of component ($/kg) / cost steel of reference ($/kg)

f_i = cost installation of component ($/kg) / cost steel of reference ($/kg)

j	Component (j = 1 to 8)	Manufacturing factor f_{mj}	Installation factor f_{ij}
1	Rotor (blades)	3.00	0.50
2	Hub (with pitch system)	0.60	0.50
3	Nacelle (with drive-train, electrical generator, power converters, yaw, etc.)	3.00	0.50
4	Tower	0.90	0.50
5	Floating platform	1.20	0.50
6	Mooring system	0.10	0.10
7	Anchor system	0.10	0.10
8	Electrical system (substation, intra-farm lines, farm-to-shore lines)	0.16	0.10

Table 4 shows the manufacturing factors f_m and installation factors f_i of the eight main components of the FOWT. Factors in Table 4 should be used by default unless a reasonable change is proposed and justified. If the new design of the FOWT does not include some of these eight components, they can be removed from the summation of the equivalent mass –eq.(7). Also, if the new design of the FOWT needs different components, new manufacturing f_m and installation f_i factors for the new components will be proposed and justified by the applicants.

The new FOWT designs proposed for this envisioned program would have to achieve the performance target described in Section D.2, and would have to be validated under the following

[42] Prices from: High Performance Conductors Inc, Nov. 2018, and MIT - Table. Material type, properties and costs.

[43] Factors based on several references, including: (1) Myhr, A., Bjerkseter, C., Ågotnes, A., Nygaard, T. (2014). *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*. Renewable Energy, Vol. 66, pp. 714-728; (2) Stehly, T., Beiter, P., Heimiller, D., Scott, G. (2018). *2017 Cost of Wind Energy Review*. Technical Report NREL/TP-6A20-72167; and (3) Fingersh, L., Hand, M., Laxson, A. (2006). *Wind Turbine Design Cost and Scaling Model*. Technical Report NREL/TP-500-40566.

conditions:

(a) Material factors f_t using Table 3. For materials not included in this Table, new material factors can be proposed and justified.

(b) Manufacturing factors f_m and installation factors f_i for the eight main components of the FOWT using Table 4. For new components, new manufacturing and installation factors can be proposed and justified. If the design does not need a particular component, it can be removed from the calculation of the equivalent mass.

(c) Water depth = 100 m

(d) Number of turbines in wind farm = 100

(e) Accepted computer tools for load calculations (OpenFast,[44] Bladed[45] or similar).

(f) Wind class I or II according to the IEC-61400 standards.[46]

(g) Sea conditions in North Atlantic.[47,48,49,50]

(h) Design Load Cases (DLCs) according to the IEC-61400-3 standards for offshore wind, including operational cases, mechanical fatigue cases and extreme load cases (five operational modes, Section C.4.1).[46]

E. Envisioned program structure

E.1. Program

Projects under the envisioned program would cover three fundamental areas: (1) radically new FOWT designs, (2) computer tools to co-design the FOWTs, and (3) real-data from full and lab-scale experiments to validate the FOWT designs and computer tools.

Projects in the first fundamental area (*New designs*) would include at least two parts: (a) a new design that achieves the envisioned program target metrics described in Section D.2 for the conditions (a to h) described in section D.3, and (b) the calculations for the design of a small-scale prototype, to be potentially developed and experimentally tested in a possible second phase of the envisioned program, if selected.

Projects in the second fundamental area (*Computer tools*) would include the elements (e1) through (e4) presented in Section C.4.2, and at least four of the remaining elements, (e5) to (e10). These computer tools, at different levels of development, could be made available for the teams in the first fundamental area (New designs).

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[44] OpenFAST. (2018). National Renewable Energy Lab, NREL. https://nwtc.nrel.gov/OpenFAST
[45] Bladed, DNV-GL, https://www.dnvgl.com/services/bladed-3775
[46] International Electro-technical Commission, IEC 61400-3, Wind turbines – Part 3: Design requirements for offshore wind turbines. https://collections.iec.ch/std/series
[47] Lee, W.T., Bales, S.L., Sowby, S.E. (1985). *Standardized wind and wave environments for North Pacific Ocean Areas*. Report, Defense Technical Information Center.
[48] Faltinsen, O. (1993). *Sea loads on ships and offshore structures*. Vol. 1. Cambridge University Press.
[49] Myhr, A., Bjerkseter, C., Ågotnes, A., Nygaard, T. (2014). *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*. Renewable Energy, Vol. 66, pp. 714-728.
[50] Jonkman, J. (2007). *Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine*. NREL/TP-500-41958.

Projects in the third fundamental area (*Experiments*) would include at least two aspects: (a) development of intelligent real-time systems to collect data from full and/or lab-scale FOWTs, and (b) development of a field data repository, publicly available, to enable validation of computer tools and FOWT new designs –see details in Section C.4.3. The projects of this area could be proposed as part of the computer tools projects.

E.2. Multidisciplinary program and project interactions

The envisioned program would require a broad range of technical communities to work together. These communities include, but are not limited to control and systems engineering, co-design, aerodynamics, hydrodynamics, electrical and mechanical systems, power electronics, electrical generators, structural engineering, naval engineering, modeling, optimization, economics, multi-scale and multi-physics computer algorithms, parallel computing, distributed sensors, intelligent signal processing and actuator networks; as well as developers of offshore wind energy systems and electrical utilities.

Applying CCD demands teams to work together in a truly multidisciplinary way –see Fig.12. Ideal teams for this envisioned program would include team members or institutions that cover the team intersections shown in Figure 12, either double or triple intersection. In addition, industry advisory boards that include wind turbine manufacturers and floating platform manufacturers would be encouraged. Applicants to this envisioned program would be required to provide details on their planned collaboration approach and justify that it would be sufficiently integrated. This would include details on:

(a) Specific team training for concurrent multi-disciplinary work, including control co-design aspects.

(b) Intellectual property solutions across the team members for key aspects of the design, computer tools and real-data.

(c) A clear definition of the input/output interfaces and iterative methodologies of the work to be developed by each team member.

(d) Project activities and meetings during the project to improve the multi-disciplinary collaboration.

(e) Project milestones that reflects this multi-disciplinary effort.

The multi-disciplinary collaboration aspects of each project are not limited to the institutions or members of each team, but is also intended to be proposed across the teams of the envisioned program.

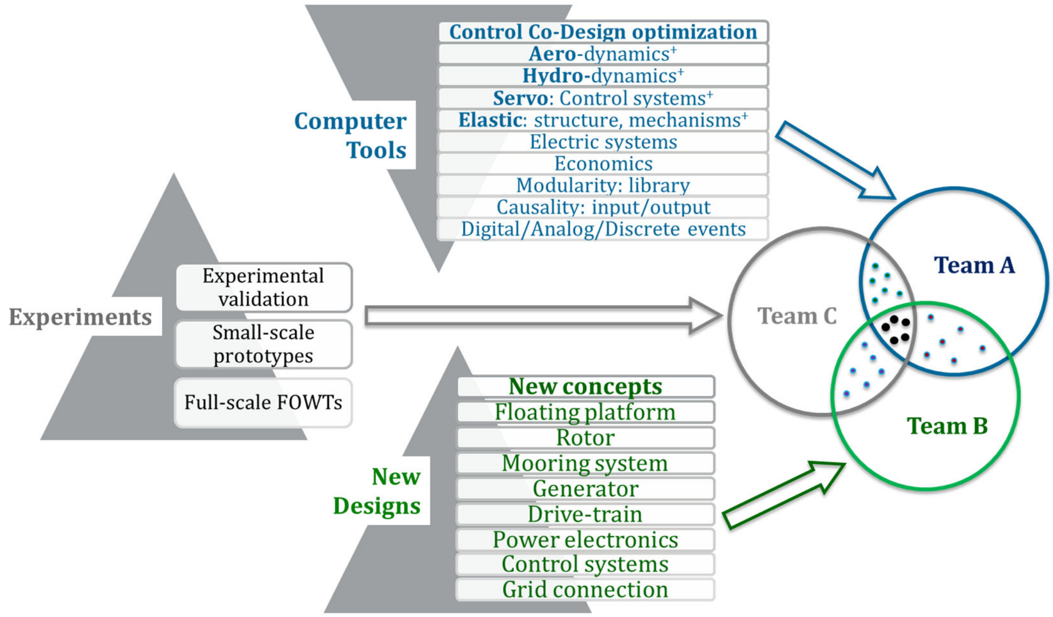

Fig. 12. Multi-disciplinary team composition.