Task49 浮体式洋上風力発電所の統合設計

Integrated Design on Floating wind Arrays (IDeA)

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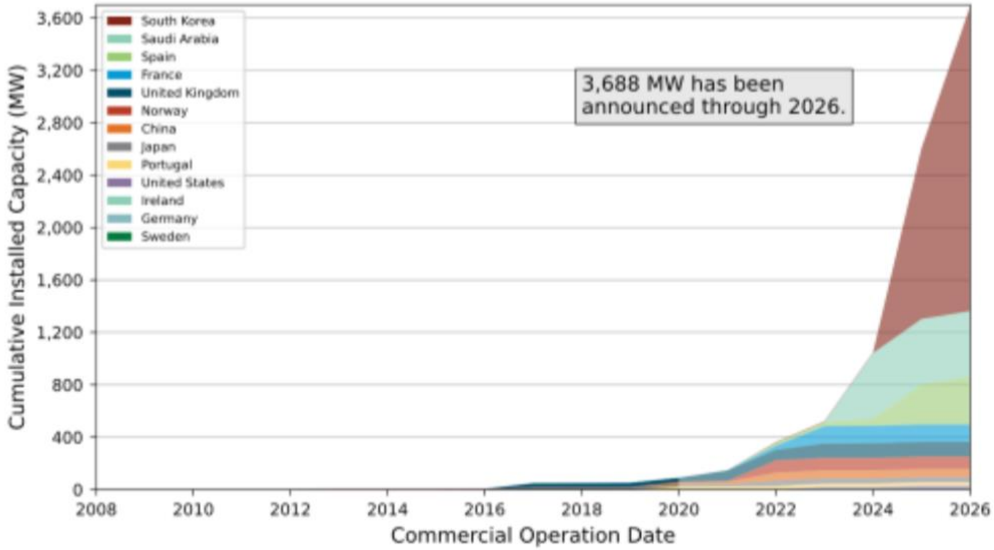
Task49 の目的

- 浮体式洋上風力発電所は2020年現在、世界で79MWが運転しているに過ぎないが、今後10年間で飛躍的な増大が期待されている。



Musiel et al., (2021)

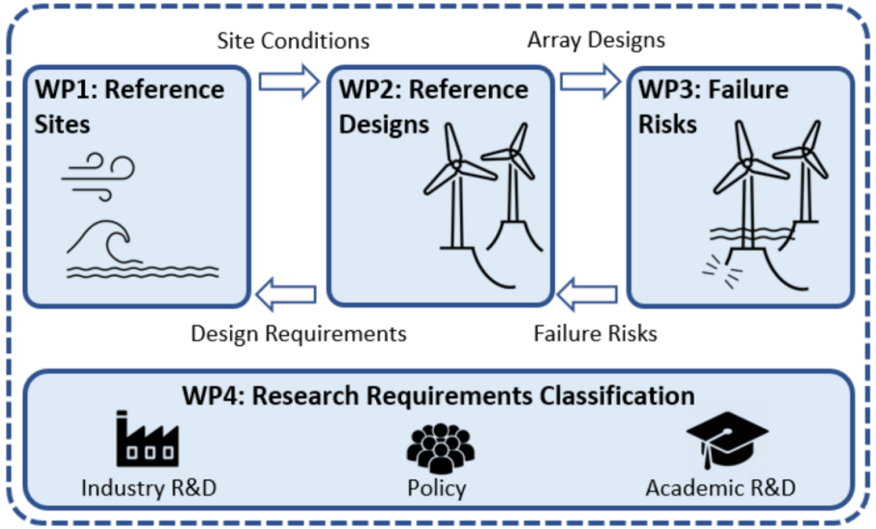
- Task49は、世界各国における浮体式洋上風力発電所の最適設計に資するため、標準的な浮体式洋上風力発電所を定義し、標準的な設計手法の枠組および設計ツールを開発する。

- WP1：標準設計条件の定義
  世界各国の観測データ、シミュレーションデータを元に、標準設計条件を定義する。

- WP2：標準発電所(Array)の定義
  風車配置、ユニット(風車-浮体)、係留方法、送電ケーブル、変電所、等を含む標準浮体式風力発電所を定義する。

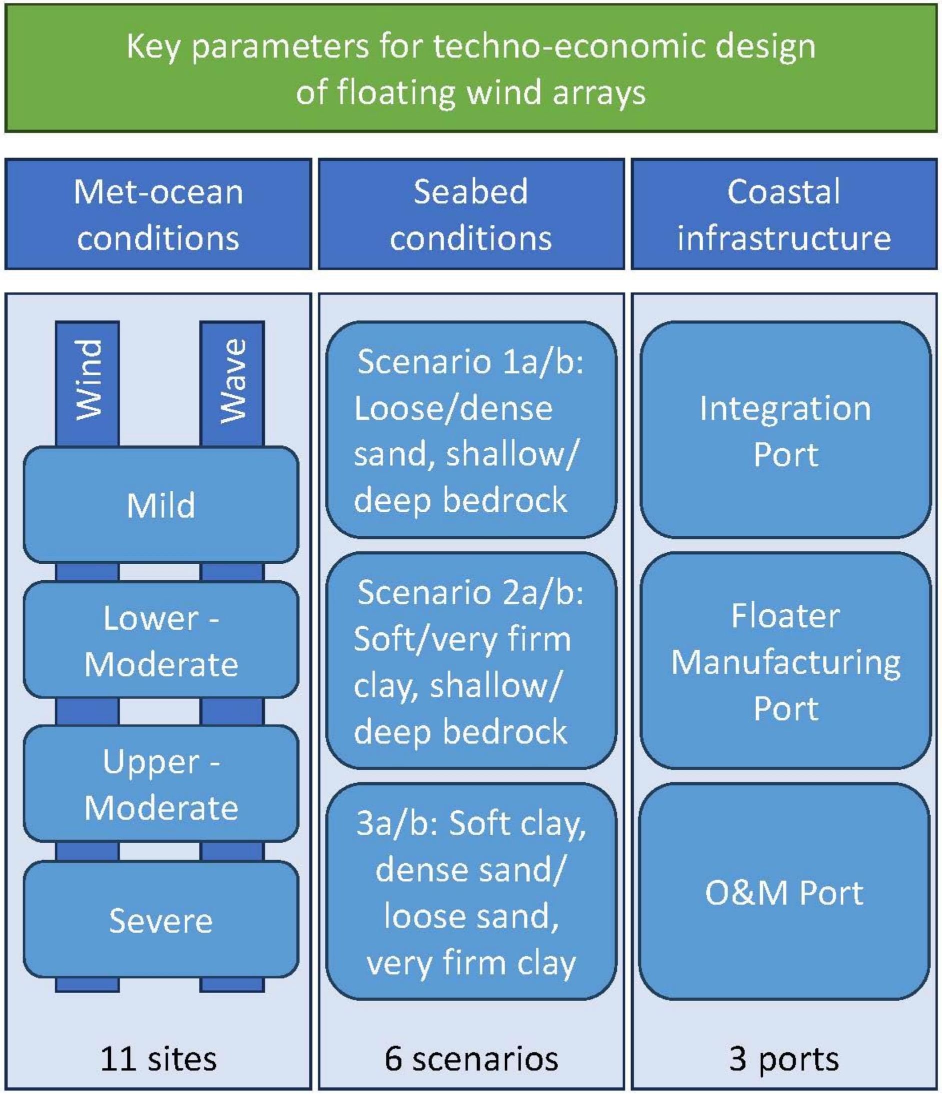
- WP3：発電所レベルでの損傷リスクと低減
  発電所レベルでの損傷モードを明らかにし、その影響を明らかにする。

- WP4：問題点の明確化
  各ワークパッケージにおける問題点を明らかにし、今後の研究課題を明らかにする。



WP1 標準設計条件の定義

- 気象海象条件
- 海底地盤条件
- 沿岸インフラ
- 環境影響
- 社会・経済影響
- 規制と許認可

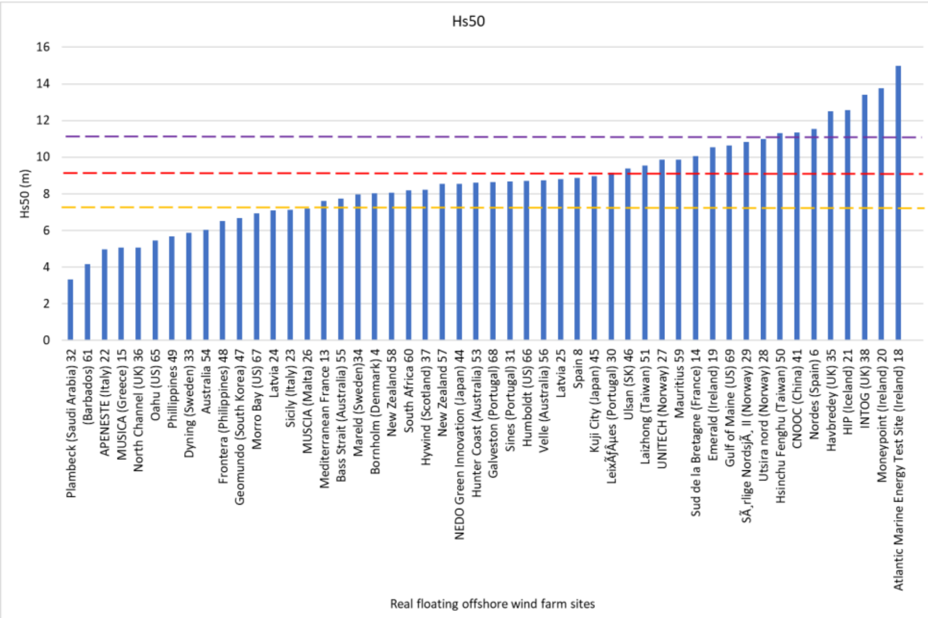


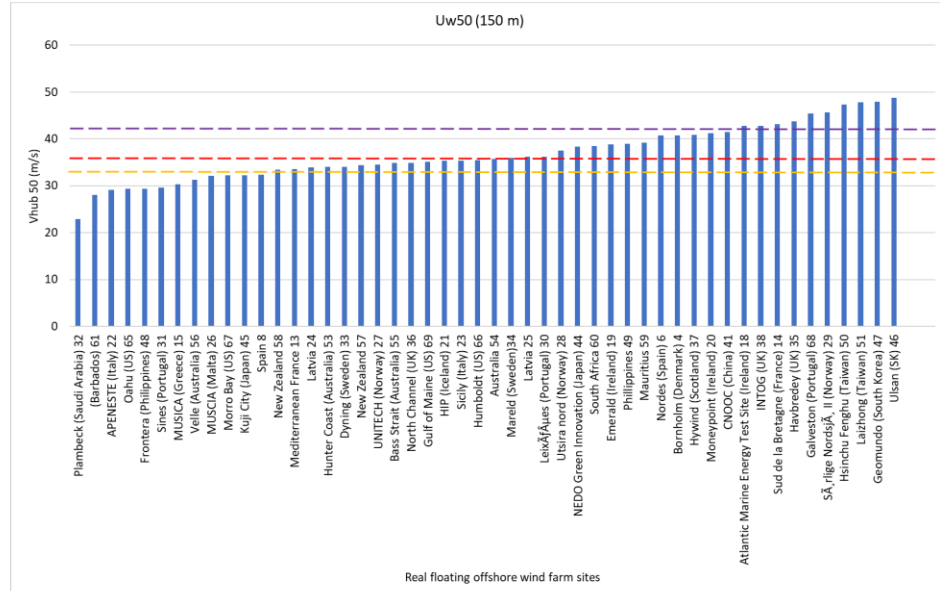
気象･海象条件の分類

- 全世界69サイトにおいて、ERA5再解析データ(気象:0.25度解像度;海象0.5度解像度)の生データを用いて、風速と波浪の極値を推定した。

- 各サイトの水深をGEBCO(GEneral Bathymetric Chart of the Oceans)データから抽出。

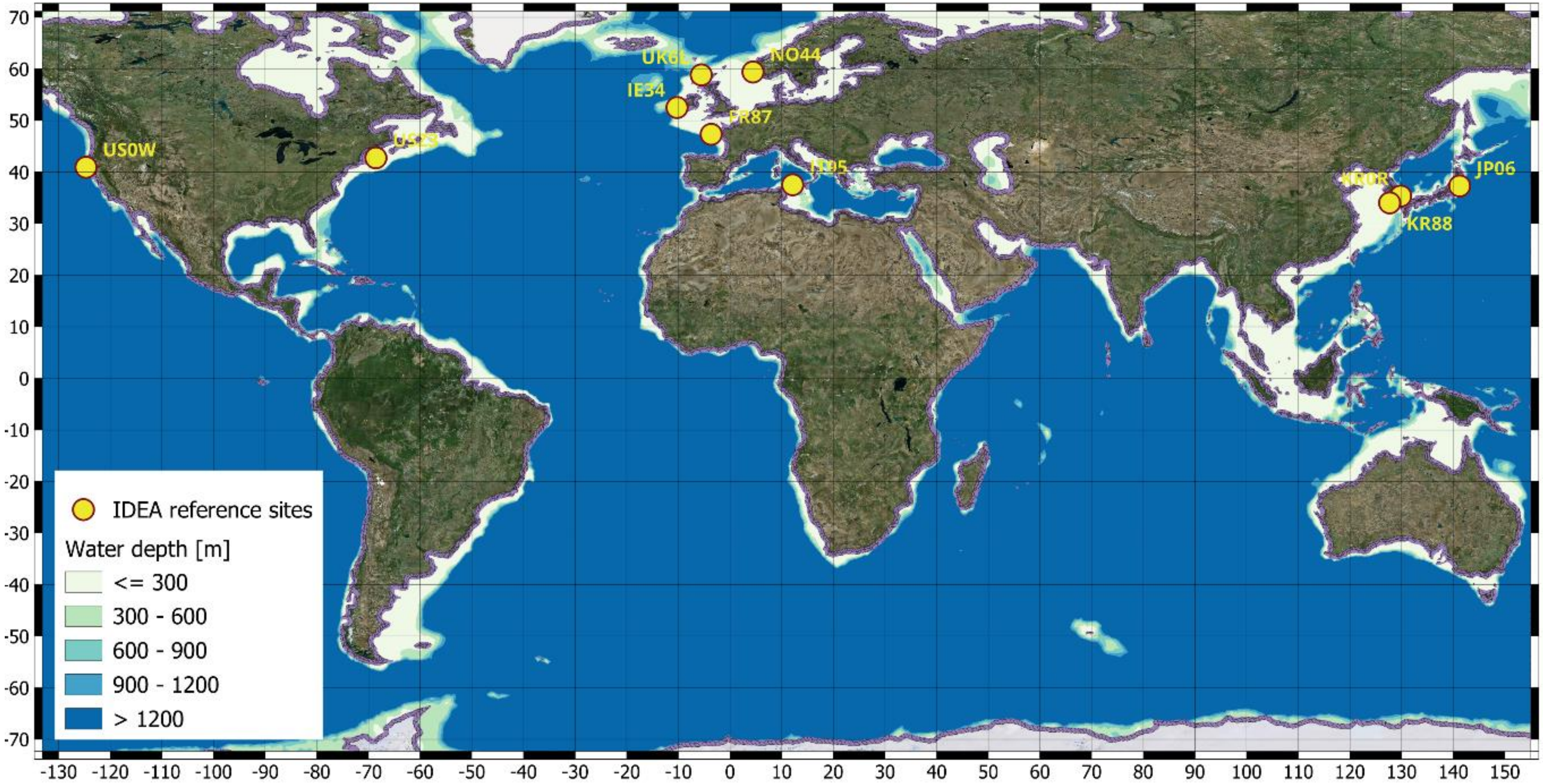
49サイトの極値の分類





Severity	Wind threshold (m/s)	Wave threshold (m)
Mild	< 33	< 7.5
Lower Moderate	33 < 36	7.5 < 9
Upper-Moderate	36 < 42	9 < 11
Severe	> 42	> 11

世界各国のサイトの紹介



サイトデータの例

ID*	Name	Latitude [deg]	Longitude [deg]	Water depth [m]	Distance from shore [km]
IT95	Hannibal	37.536	12.12	-353	35
US0W	Humboldt	40.928	-124.708	-707	43.8
KR0R	Ulsan	35.344722	129.841389	-188	32
IE34	MoneyPoint One	52.519	-10.276	-102	23.4
UK6L	Havbredey	58.84328	-5.580929	-91	41.6
JP06	Fukushima	37.311	141.251	90	19.4
NO44	Utsira Nord	59.411	4.433	-273	42.4
USZ3	Gulf of Maine	42.755	-68.583	-148	138
KR88	Geomundo	34.026	127.7	-70	47
FR87	Sud de la Bretagne II	47.325	-3.659	-94	30.7

WP2:標準風力発電所の考え方

Feature	Greatest Interest	Secondary Interest
Layout	Regular rectangular	Triangular, irregular, optimized
Turbine size	15 MW	~20 MW or a range of sizes (12, 15, 18)
Turbine number	Multiple array sizes in the range of 20-100 turbines	As few as 7-10 turbines
Platform type	Steel semisubmersible	Spars, TLPs, barges, concrete construction
Mooring configuration	All basic types (cat-TLP)	Different rope materials, shared configurations, load reducers, multiple anchor types, seabed dependence
Dynamic Cable Configuration	Lazy wave	Catenary free-hanging, suspended W, etc.
Intra-array cable rating	66 kv and 132 kV	
Depth	Shallow, medium, and deep options	
Misc	Seabed changes and anchor/mooring implications	Substation, cable connections, and export cable

Scenario	Shallow	Intermediate	Deep
Key features	Shallow-water mooring/cabling design challenges and innovations	Seabed feature constraints on anchor positions, and innovations on anchoring	Deep-water constraints on mooring layout and turbine spacing, use of W-shaped cables and deep-water mooring innovations
Design variants (sequential)	V1: uniform *Secondary options*: V2: depth gradient with adapted mooring designs V3: spring option	V1: uniform *Secondary options*: V2: complex seabed, adapted layout and anchor positions V3: shared anchor option V4: cable layout designs	V1: uniform *Secondary options*: V2: depth gradient with adapted layout, moorings, cables V3: shared mooring option V4: TLP option
Metocean	Sørlige Nordsjø II	Utsira Nord	Humboldt
Depth	60 meters (m) *Secondary option*: sloped 40–120 m	300 m *Secondary option*: irregular 200–400 m	800 m *Secondary option*: irregular 600–1,000 m
Seabed	Generic	Generic *Secondary option*: irregular with bedrock/ridges	Generic

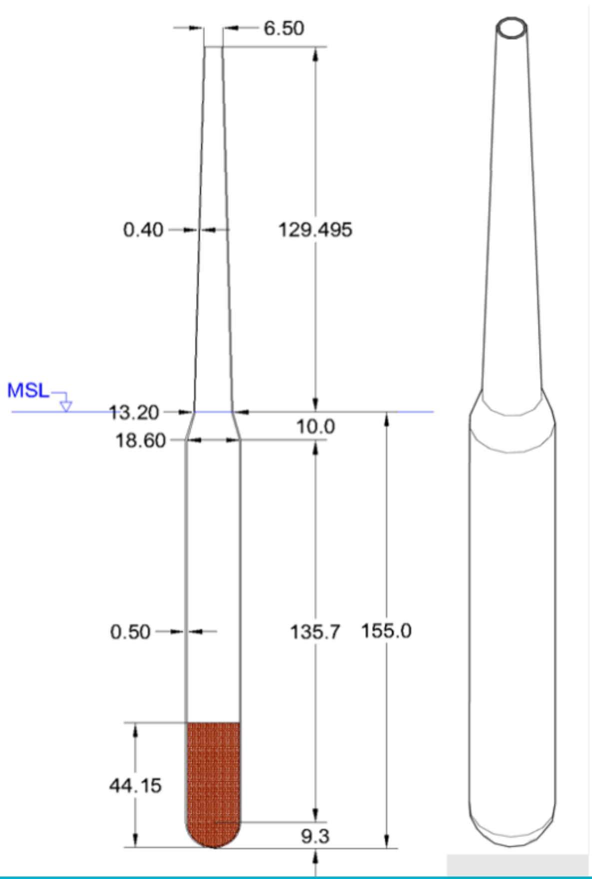
Scenario	Shallow	Intermediate	Deep
Array layout	Rectangular	Rectangular *Secondary option*: varied	Rectangular *Secondary option*: varied
Platform type	Semi	Semi or Spar *Secondary option*: TLP	Semi or Spar *Secondary option*: TLP
Mooring configuration	Semi-taut shallow water	Catenary chain (+wire?) *Secondary option*: semi-taut intermediate water	Taut synthetic *Secondary options*: shared taut, TLP
Mooring layout	Regular	Regular *Secondary option*: varied	Regular
Anchors	Drag embedment *Secondary option*: suction pile	Drag embedment *Secondary option*: shared suction pile	Suction pile *Secondary option*: drag embedment
Cable configuration	Lazy wave	Lazy wave	Fully suspended
Cabling layout	Regular	Regular or irregular if seabed constraints	Regular

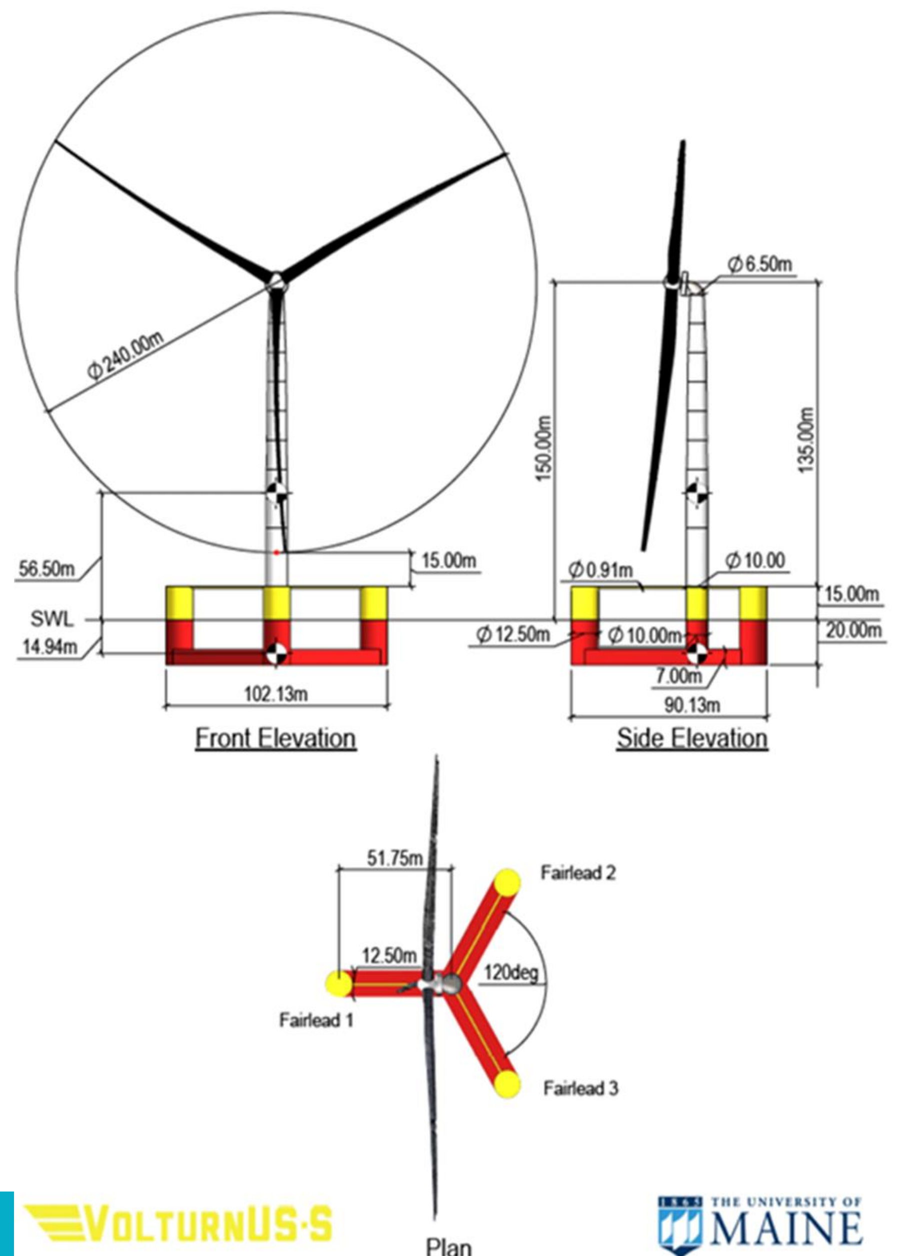
- NREL 5MW, DTU 10MW などいくつかの公的に利用可能な風車モデルがあるが、IEA 15MW (Task37) 風車を標準風車として考える。

Parameter	Value
Power rating (MW)	15
Turbine class	International Electrotechnical Commission (IEC) Class 1B
Specific rating (watts per square meter [W/m^2])	332
Rotor orientation	Upwind
Cut-in wind speed (meters per second [m/s])	3
Rated wind speed (m/s)	10.59
Cut-out wind speed (m/s)	25
Design tip-speed ratio	9
Minimum rotor speed (rpm)	5
Maximum rotor speed (rpm)	7.56
Maximum tip speed (m/s)	95
Rotor diameter (m)	240
Hub height (m)	150
Hub diameter (m)	7.94
Hub overhang (m)	11.35
Rotor precone angle (deg)	-4
Blade prebend (m)	4
Blade mass (tonnes [t])	65
Drivetrain	Direct drive
Shaft tilt angle (deg)	6
Rotor-nacelle assembly mass (t)	1,017

標準浮体

- メイン大学(アメリカ) VolturnUS-S　セミサブ浮体
- カタルーニャ工科大学(スペイン) Wind Create スパー浮体





浮体式風力発電所を対象に故障モード影響解析(FMEA)を実施した。

リスク優先度(RPN)を下式で定義。

$$RPN = S(Severity) \times O(Occurrence) \times D(Detection)$$

Table 1: Severity matrix used for the FOWT. Modified from *[14]*

Severity class	Personnel Safety	Environmental Impact	Asset Integrity	Operation	Ranking
Catastrophic	1 or more fatalities	Significant environmental impact	Damage > 30 M €, total loss	Total Operational Loss, replacement	5
Critical	Multiple Major Injuries	Critical damage/pollution, minimal effect of control measures	Major Damage [10-30 M€]	Major repair needed (operational loss from 1 day to 1 week	4
Major	Multiple Minor Injuries, Major Injury	Major damage/pollution, low effect of control measures	Localized Damage [1-10 M€]	Minor replacement needed (operational loss < 1 day)	3
Marginal	Minor Injury (First Aid)	Minor damage/spillage, good effect of control measures	Minor Damage [0.1-1 M€]	Short Operational Loss (few hours)	2
Minor	No Injury	No damage/contamination	Negligible damage < 100 K€	Minimal Operational Loss	1

Table 2: Occurrence matrix used for the component level FMEA. Modified from [14]

Probability	Probability of failure	Possible annual failure rates	Ranking
Very frequent	Almost inevitable failures	>= 1 in 8	5
Probable	Repeated failures	From 1 in 8 to 1 to 80	4
Occasional	Occasional failures	From 1 in 80 to 1 in 400	3
Remote	Relatively few failures	From 1 in 400 to 1 in 150,000	2
Highly Unlikely	Highly unlikely failures	=< 1 in 150,000	1

Table 3: A detection matrix is to be used for the component level FMEA. Modified from [14]

Detection	Criteria: Likelihood of detection by design control	Ranking
Very Low	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control	5
Low	Low chance: the design control will detect a potential cause/mechanism and subsequent failure mode	4
Moderate	Moderate chance: the design control will detect a potential cause/mechanism and subsequent failure mode	3
High	High chance: the design control will detect a potential cause/mechanism and subsequent failure mode	2
Very High	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode	1

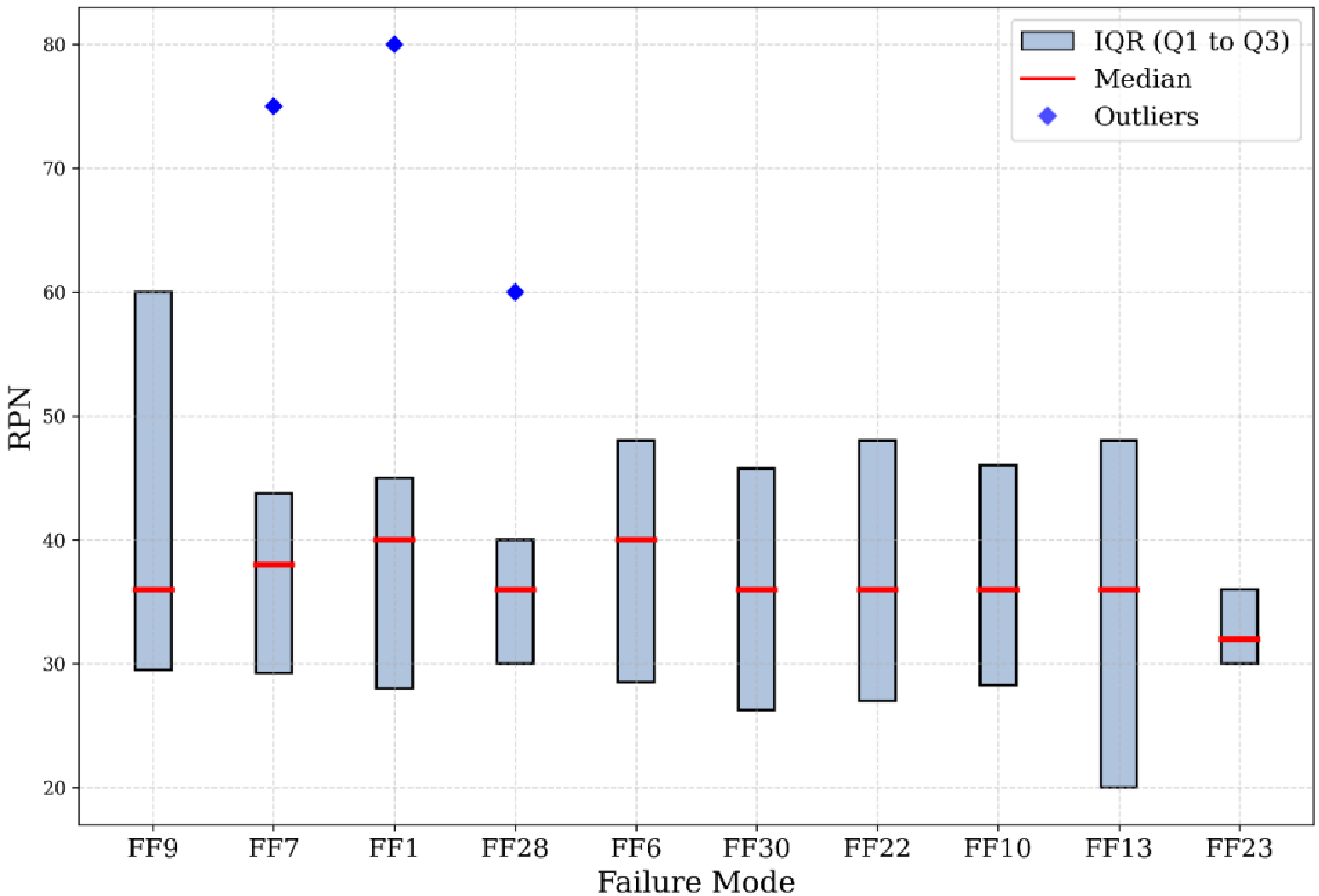
分析手法

専門家によるワークショップを開催し、各故障モードの影響を定量化した。

Table 1: Participant background for the FMEA method

Sector	Years of Experience	Relevant Expertise
R&D	10 (incl. O&G)	10 projects related to condition and structural health monitoring offshore
Risk consultancy	15	Risk identification, and quantification for offshore wind, wave, tidal, and Ocean Thermal Energy Conversion (OTEC)
Insurance	36	Structuring risk finance solutions, optimizing risk finance solutions for companies with non-standard/ prototypical assets
Academia	15	Renewables with over 7 years offshore wind, tidal, and wave systems
Development	22 (incl. O&G)	Development of aerodynamics codes, realization of fully coupled simulations (servo-aero-hydro-elastic).
Industry	> 15	Offshore structural engineering, with the last 11 years dedicated to offshore wind
Research Institute	11.5	Development & Certification of tower structures, hub structure of a floating wind turbine Fatigue calculation and measurement analysis of a floating support structure & tower
Floating Development	2	Development stages of projects, both fixed and floating offshore wind farms, located in Spain, Italy, Philippines and Australia.

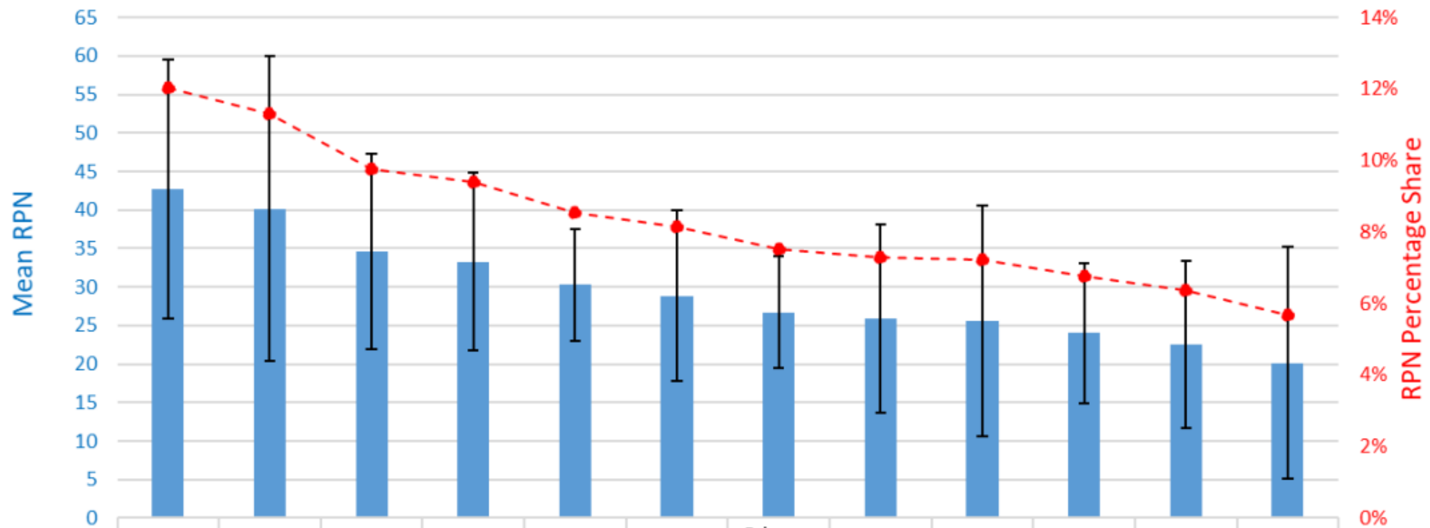
例：浮体の故障モード



FF9　浮体構造や溶接へのクラック

FF7　浮体構造の腐食，疲労

風力発電所レベルへの影響



	Primary structure & Welding-Operation	All structures-Design	All structures & Welding-Maintenance	Secondary structure-Operation	All structures-Design	Secondary structure-Design	Primary structure & Welding-Environmental condition	All structures-Environmental condition	Primary structure -Design	All structures-Environmental condition	Primary structure & Welding-Operation	All structures-Operation
Failure mode-Failure cause	43	40	35	33	30	29	27	26	26	24	23	20
RPN Percentage	12%	11%	10%	9%	9%	8%	8%	7%	7%	7%	6%	6%

Phase 1 のまとめ

IEA Wind Task 49の第1フェーズは、2021年12月から2026年5月まで実施された。本フェーズには12カ国が参加し、以下の4つのワークパッケージ（WP）に重点的に取り組んだ。

WP1 世界の浮体式洋上風力発電プロジェクト（パイプライン）を代表する一連のサイト条件の選定・整理
WP2 典型的なサイト条件および技術タイプに対応する、参照用アレイ（発電所群）設計の策定
WP3 アレイ・レベルにおける故障リスク、その影響、および緩和策の体系化
WP4 重要な技術革新の機会、ならびに海洋空間計画および研究に関する要件の特定

残された課題

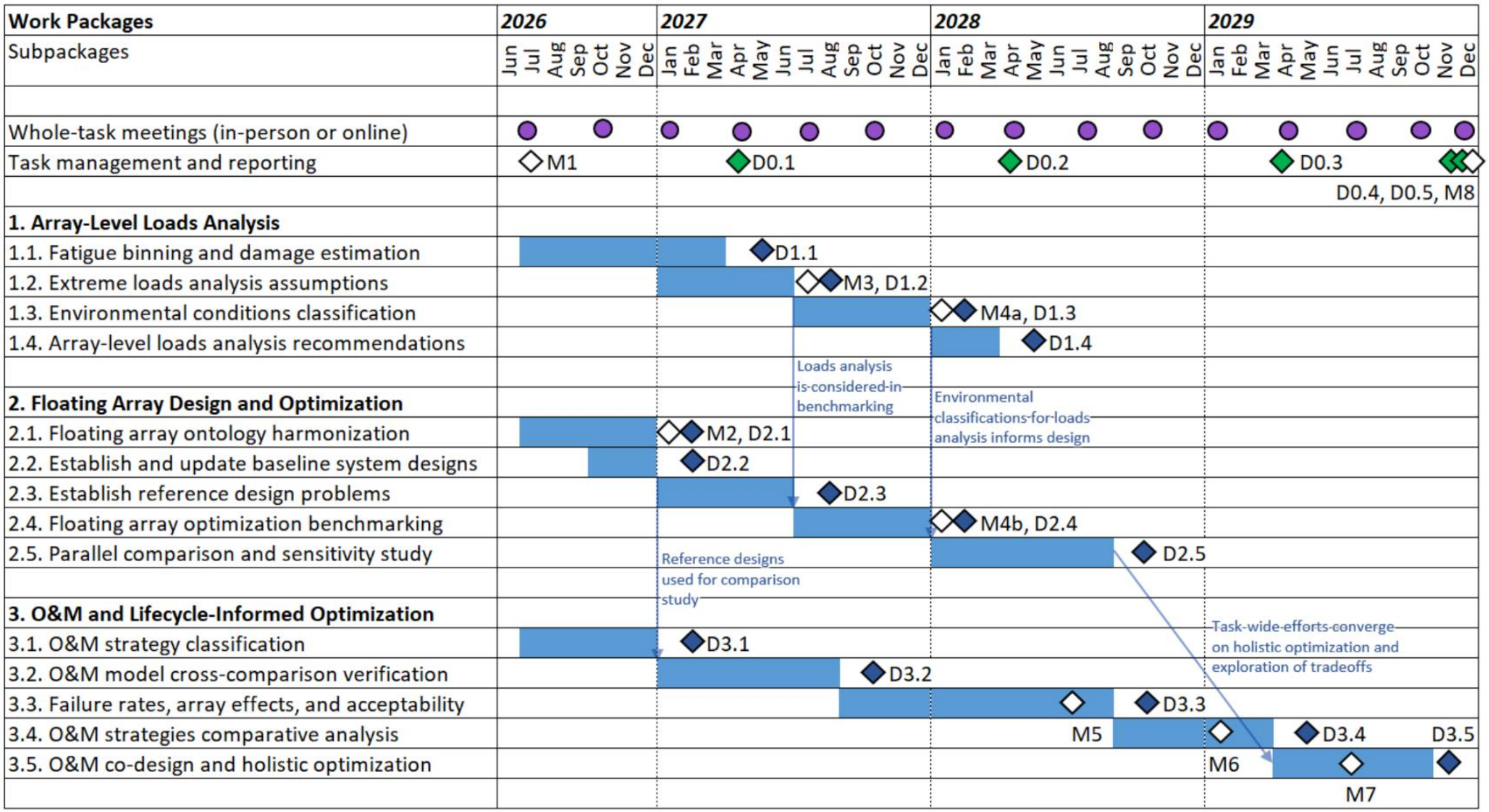
- より多様かつ高度な標準設計モデルが必要である。
- 浮体式風力発電所レベルでの荷重解析における不確実性がある。
- 浮体式風力発電所の故障リスク、信頼性、およびO&M（運用・保守）の複雑さは特に大きな問題である。

Task 49のフェーズ2は、以下の分野に重点を置く3つのワークパッケージで構成される。

WP1　大型浮体式洋上風力発電アレイの荷重解析に向けた、信頼性が高く実用的な手法の確立
WP2 浮体式アレイの最適化に向けた共通リソースの整備、ベンチマーク、および感度解析
WP3 O&M（運用・保守）戦略の特性評価と選定基準の策定、ならびにより包括的なプロジェクト意思決定を可能にするための設計判断との連携

また、本タスクでは、ワークパッケージを横断するいくつかの共通テーマについても検討を行います。具体的には、アレイ内での相互干渉の影響、耐用期間を通じた気象・海象条件に対する気候変動の影響、そして設計やO&Mの標準化を可能にする環境条件の標準化の活用などが含まれる。

Work Package Structure & Tentative Schedule



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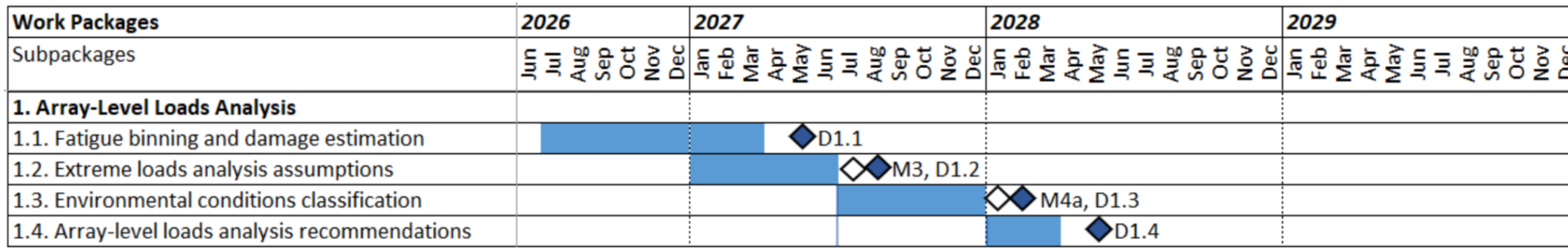
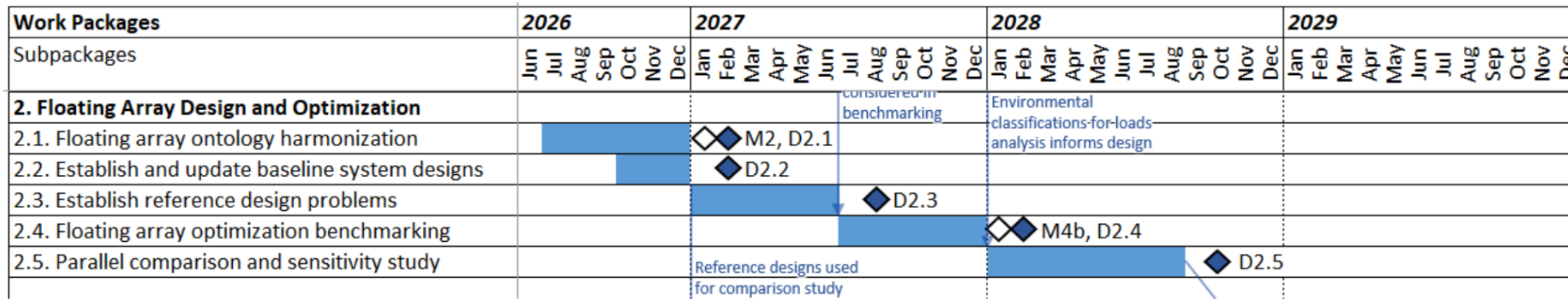
WP1: Array-level loads analysis



Subpackage	Type of collaboration	Main output / deliverable	Lead
1.1. Fatigue binning and damage estimation	Workshops, comparison/competition	Report/paper on combined fatigue analysis comparison results	Markel Penalba (Mondragon)
1.2. Extreme loads analysis assumptions	Workshops, comparison/competition	Report/paper on extreme conditions alternatives and loads comparison results	Ajit Pillai (Exeter)
1.3. Environmental conditions classification	Formulate classifications, divide up regional data processing	Report/paper describing the environmental classes and a dataset of their spatial distribution	Maurizio Collu (Strathclyde)
1.4. Array-level loads analysis recommendations	Workshops, consensus	Report on combined array level loads analysis recommendations	WP1.1-1.3 leads

日本からの参加者：　山口(足利大学)，種本(清水建設)

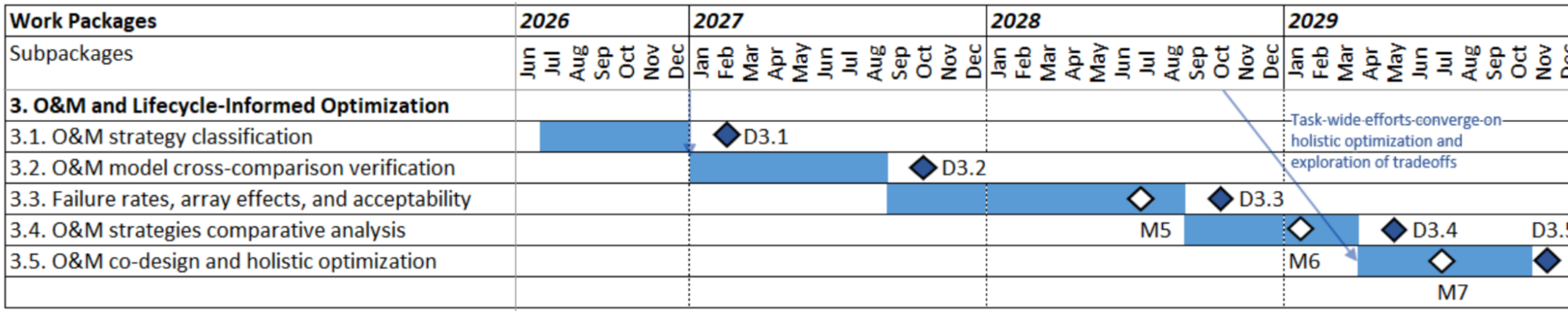
WP2: Floating Array Design and Optimization



Subpackage	Type of collaboration	Main output / deliverable	Lead
2.1. Floating array ontology harmonization	Workshops, coding, user feedback	Schema files and documentation for updated floating wind array ontology	Matt Hall (SINTEF), ?
2.2. Establish and update baseline system designs	Concensus, parallel efforts, review	Repository updates of reference/baseline design input files and documentation	TBD
2.3. Establish reference design problems	Workshops, concensus	Report/paper describing the reference design problems and associated definition files	TBD (Matt?)
2.4. Floating array optimization benchmarking	Comparison/competition	Report/paper summarizing benchmarking results and dataset of optimized design files	Ajit Pillai (Exeter)
2.5. Parallel comparison and sensitivity study	Parallel effort, comparison	Report on combined optimization sensitivity study results	TBD (Ajit? Matt?)

日本からの参加者：　望月、浜野(FLOWRA)

WP3: O&M and Lifecycle-Informed Optimization



Subpackage	Type of collaboration	Main output / deliverable	Lead
3.1. O&M strategy classification	Workshops, consensus	Report/paper detailing the O&M strategy classifications	Antonio Donatelli (ENEA)
3.2. O&M model cross-comparison verification	Parallel effort, comparison	Report/paper summarizing O&M model comparison results along with results dataset	Markel Penalba (Mondragon)
3.3. Failure rates, array effects, and acceptability	Workshops, consensus	Report/paper on state of the art in floating array failure analysis and acceptable risks	TBD
3.4. O&M strategies comparative analysis	Parallel effort, comparison	Report/paper on design-dependent, condition-based O&M strategy selection	TBD (Antonio, Markel?)
3.5. O&M co-design and holistic optimization	(to be determined)	Report/paper on design-O&M linkages and tradeoffs and decision-making recommendations	TBD (Matt?)

日本からの参加者： 望月、浜野(FLOWRA)