# Part 3

Impact of Improvement on Characterisation and Modelling - 25mins

# RealTide Project

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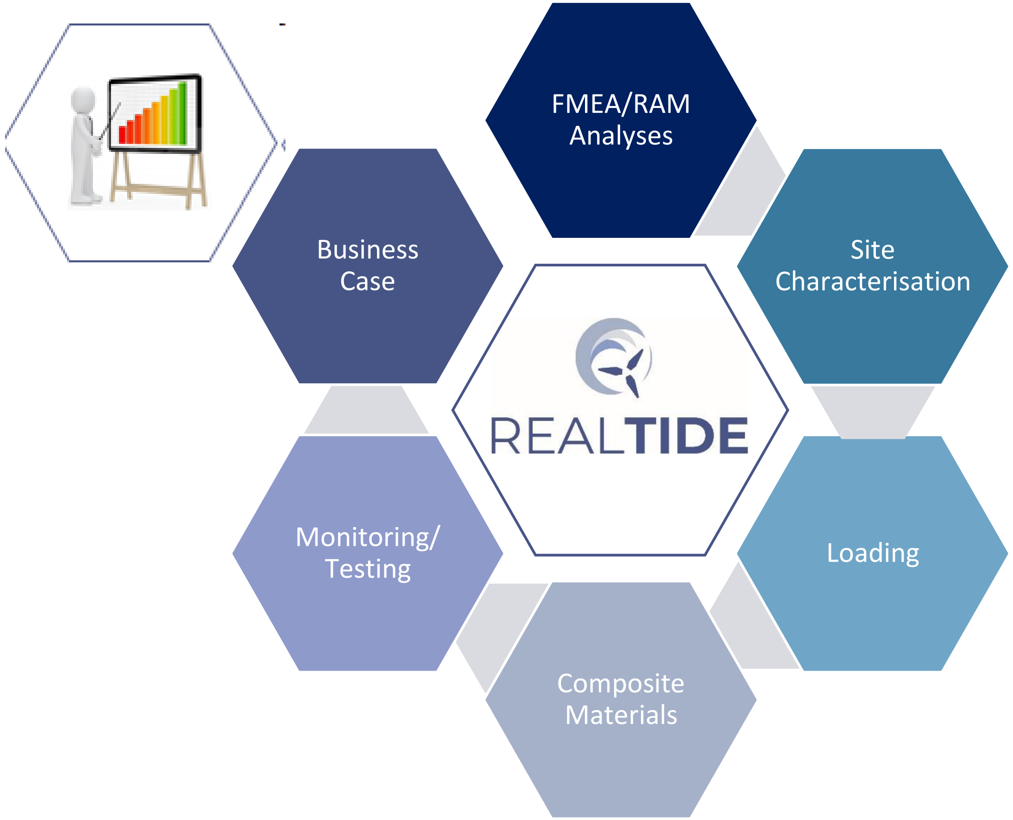


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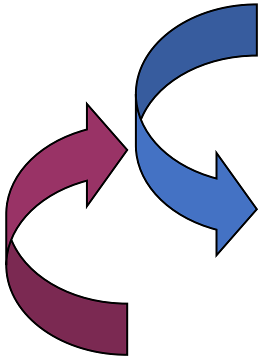
# RealTide business case: Methodology

## Cost modelling

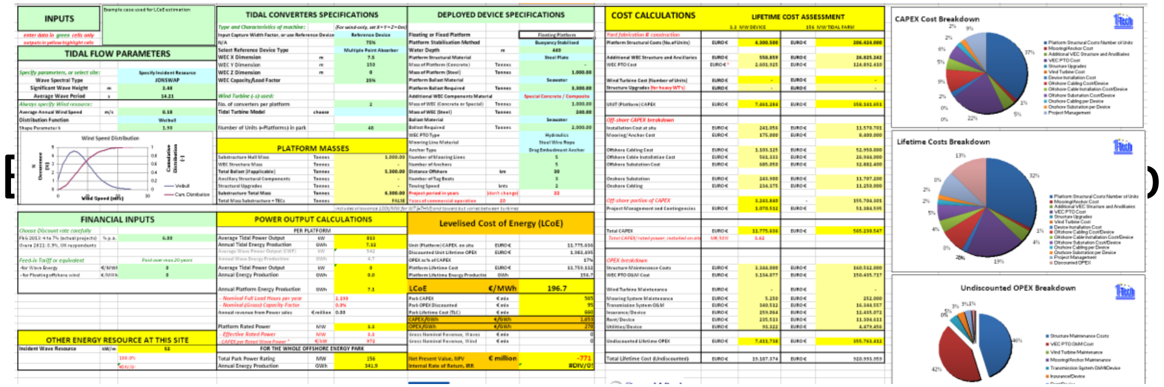
- Bottom up
- Costing of arrays and farms
- Detailed… but not excessive
- Estimates LCoE from resource, construction & operations cost
- Immediate on-screen feedback facilitates sensitivity studies
- Allows quantifying role of Opex on a par with that of Capex

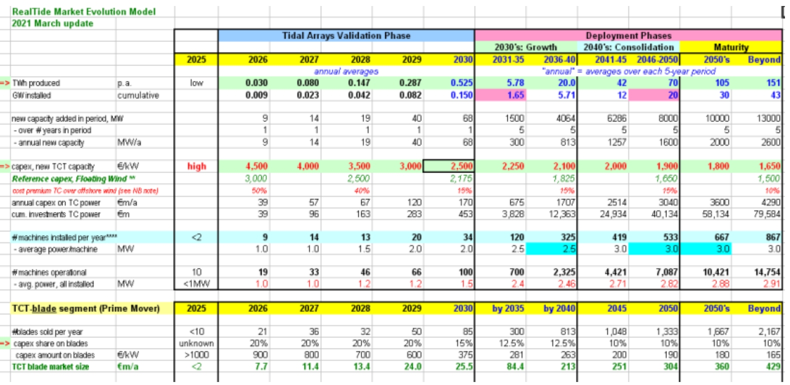


## Market evolution modelling

- Top down, calibrated by costing-model data
- Rational approach to evolution of markets
- Assumes current SET-Plan targets reached: LCoE = 150 €/MWh by 2025, 100 by 2030
- Allows creating scenarios with varied sensitivity to deployment parameters
- Baseline comparison Capex is innovative off-shore wind (i.e. deepwater/floating)

E … ooks with



# Snapshot: Costing model (”Main” screen inputs)

## INPUTS

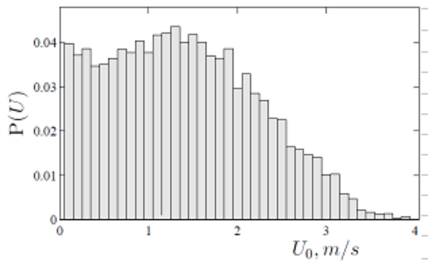
*enter data in green cells only*
*outputs in yellow highlight cells*

TIDAL STREAM: Draft pre issue version.
Early tidal farm of 50-100MW capacity. Models 20-unit, 100MW farm. Turbine capex €2m/MW. 3km offshore - No offsh. substation. 50m deep.

### TIDAL FLOW PARAMETERS

| | | |
|---|---|---|
| Mean Annual Power Density | 2.2 | kW/m2 |
| Mean Annual Current Speed | 2.0 | m/s |
| Site: | Generic high energy site | |

*Tidal Current Speed distribution:*




| | | |
|---|---|---|
| Significant Impact Factor (SIF) | 20% | (assumed) |

### ENERGY CONVERTERS SPECIFICATIONS

| | | |
|---|---|---|
| *Wave Energy Converters (WEC's):* | | *(For wind-only, or Tidal, X = Y = Z = 0m)* |
| Input Capture Width Factor, or use Reference Device | | Reference Device |
| N/A | | 75% |
| Select Reference Device Type | | Multiple Point Absorber |
| WEC X Dimension | m | 0 |
| WEC Y Dimension | m | 0 |
| WEC Z Dimension | m | 0 |
| WEC Capacity/Load Factor | | 25% |
| *Tidal Converter used (category)* | | |
| RealTide concept | | 1 |
| Number of Units (=connection points) in park | | 20 |

### PLATFORM SPECIFICATIONS

| | | |
|---|---|---|
| Floating or Fixed Platform | | Floating or Bottom-fixed |
| Platform Stabilisation Method | | Mooring Line Stabilised |
| Water Depth | m | 50 |
| Platform Structural Material | | Steel Plate |
| Mass of Platform (Concrete) | Tonnes | - |
| Mass of Platform (Steel) | Tonnes | 500.00 |
| Platform Ballast Material | | Seawater |
| Platform Ballast Required | Tonnes | - |
| Additional WEC Components Material | | |
| Mass of WEC (Concrete or Special) | Tonnes | - |
| Mass of WEC (Steel) | Tonnes | - |
| WEC Ballast Material | | Seawater |
| WEC Ballast Required | Tonnes | - |
| WEC PTO Type | | Direct Drive |
| Mooring Line Material | | Chain |
| N/A | | Drag Embedment Anchor |
| N/A | | 5 |
| N/A | | 5 |
| Distance Offshore | km | 3 |
| Special Vessel cost, Tug Boat Equivalents (TBE's) | | 30 |
| Towing Speed | knts | 2 |
| Project period in years | | 22 |
| Years of commercial operation | 20 | |

### PLATFORM MASSES

| | | |
|---|---|---|
| Substructure or Hull Mass | Tonnes | 500.00 |
| WEC Structure Mass | Tonnes | - |
| | Tonnes | - |
| Ancillary Structural Components | Tonnes | - |
| Structural Upgrades (if required) | Tonnes | - |
| Substructure Total Mass | Tonnes | 500.00 |
| Total Mass Substructure + Turbine(-s) | Tonnes | 1,000.00 |

*includes allowance 100t/MW for WT (=THM) and towers but varies between turbines*

### FINANCIAL INPUTS

| | | |
|---|---|---|
| Simplified WACC | % p.a. | 6.00 |

*Not used but reserved for future extension to multi-use*

### OTHER ENERGY RESOURCES AT THIS SITE

| | | |
|---|---|---|
| Incident Wave Resource | kW/m | 5 or less |
| Mean Wind Speed | m/s | 6.0 |
| *Weibull Shape parameter k* | | 2.0 |

### POWER OUTPUT CALCULATIONS

PER PLATFORM

| | | |
|---|---|---|
| Average Tidal Power Output | kW | 1993 |
| Annual Tidal Energy Production | GWh | 17.5 |
| Annual Platform Energy Production | GWh | 17.5 |
| *- Nominal Full Load Hours per year* | | 3,492 |
| *- Nominal (Gross) Capacity Factor* | | 39.9% |
| Annual revenue from Power sales | € million | |
| Rated Power (per connection point) | MW | 5.0 |

FOR THE WHOLE OFFSHORE ENERGY PARK

| | | |
|---|---|---|
| Total Park Power Rating | MW | 100.0 |
| Annual Energy Production | GWh | 349.2 |

### Levelised Cost of Energy (LCoE)

| | | |
|---|---|---|
| Unit (Platform) CAPEX, on site | EURO € | 16,425,384 |
| Discounted Unit Lifetime OPEX | EURO € | 6,752,044 |
| OPEX as % of CAPEX | | 41% |
| Platform Lifetime Cost | EURO € | 23,177,428 |
| Platform Lifetime Energy Productio | GWh | 384.1 |
| **LCoE** | **€/MWh** | **150.1** |
| Park CAPEX | € mln | 329 |
| Park OPEX Discounted | € mln | 135 |
| Park Lifetime Cost (TLC) | € mln | 464 |
| CAPEX/GWh | €/GWh | 941 |
| OPEX/GWh | €/GWh | 387 |
| Gross Nominal Revenue, Waves | € mln | 0 |
| Gross Nominal Revenue, Wind | € mln | 0 |
| Net Present Value, NPV | € million | NA |
| Internal Rate of Return, IRR | | NA |

## Tidal arrays

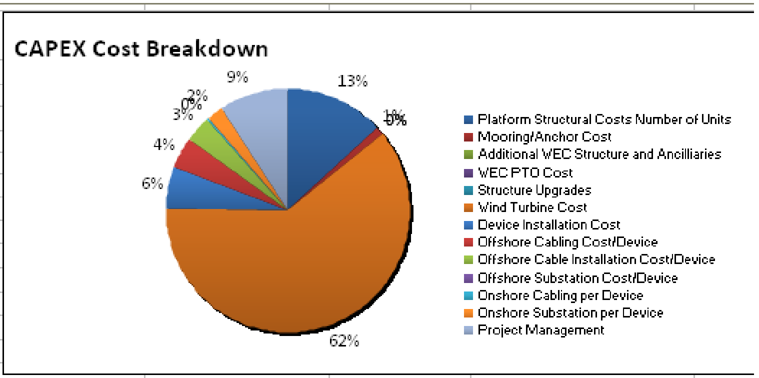
- Arrays consist of five 2-MW installations (twin turbines)
- Costing similar for fixed (e.g. monopile or GBS) or floating

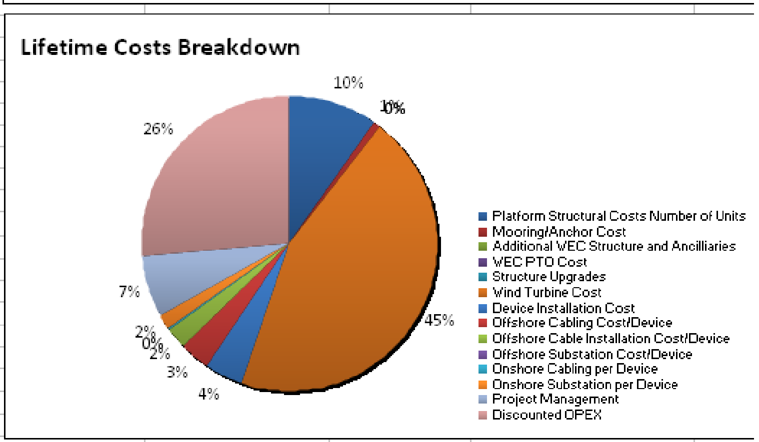
## Early-stage Tidal Farms

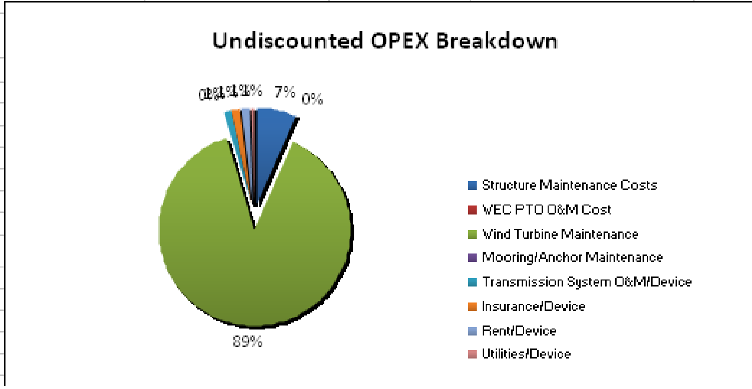
- Farms consist of at least 2 x 2MW rated turbines per connection point
- Typically 100MW, using twenty 5-MW installations
- Snapshot is for early tidal farm that (just) reaches the 2025 SET-Plan target for tidal

# Snapshot: Costing model (”Main” screen outputs)

| COST CALCULATIONS | | LIFETIME COST ASSESSMENT 5.0 MW PLATFORM | | 100 MW OFFSHORE ENERGY PARK |
|---|---|---|---|---|
| *Yard fabrication & construction* | | | | |
| Platform Structural Costs (No.of Units) | EURO € | 2,150,250 | EURO € | 43,005,000 |
| Additional WEC Structure and Ancillaries | EURO € | - | EURO € | - |
| WEC PTO Cost | EURO € | - | EURO € | - |
| Wind Turbine Cost (Number of Units) | EURO € | 10,000,000 | EURO € | 200,000,000 |
| Structure Upgrades (for heavy WT's) | EURO € | - | EURO € | - |
| UNIT (Platform) CAPEX | EURO € | 12,150,250 | EURO € | 243,005,000 |
| *Off-shore CAPEX breakdown* | | | | |
| Installation Cost at site | EURO € | 921,456 | EURO € | 18,429,125 |
| Mooring/ Anchor Cost | EURO € | 196,061 | EURO € | 3,921,216 |
| Offshore Cabling Cost | EURO € | 700,000 | EURO € | 14,000,000 |
| Offshore Cable Installation Cost | EURO € | 529,400 | EURO € | 10,588,000 |
| Offshore Substation Cost | EURO € | - | EURO € | - |
| Onshore Substation | EURO € | 375,000 | EURO € | 7,500,000 |
| Onshore Cabling | EURO € | 60,000 | EURO € | 1,200,000 |
| *Off-shore portion of CAPEX* | | 2,781,917 | - | 55,638,341 |
| Project Management and Contingencies | EURO € | 1,493,217 | EURO € | 29,864,334 |
| Total CAPEX | EURO € | 16,425,384 | EURO € | 328,507,675 |
| *Total CAPEX/rated power, installed on site* | M€/MW | 3.29 | | |
| *OPEX breakdown* | | | | |
| Structure Maintenance Costs | EURO € | 1,672,000 | EURO € | 33,440,000 |
| WEC PTO O&M Cost | EURO € | - | EURO € | - |
| Tidal Turbine Maintenance | EURO € | 22,352,697 | EURO € | 447,053,944 |
| Mooring System Maintenance | EURO € | 5,882 | EURO € | 117,636 |
| Transmission System O&M | EURO € | 366,467 | EURO € | 7,329,344 |
| Insurance/ Device | EURO € | 361,358 | EURO € | 7,227,169 |
| Rent/ Device | EURO € | 328,508 | EURO € | 6,570,154 |
| Utilities/ Device | EURO € | 143,484 | EURO € | 2,869,680 |
| Undiscounted Lifetime OPEX | EURO € | 25,230,396 | EURO € | 504,607,927 |
| Total Lifetime Cost (Undiscounted) | EURO € | 41,655,780 | EURO € | 833,115,602 |



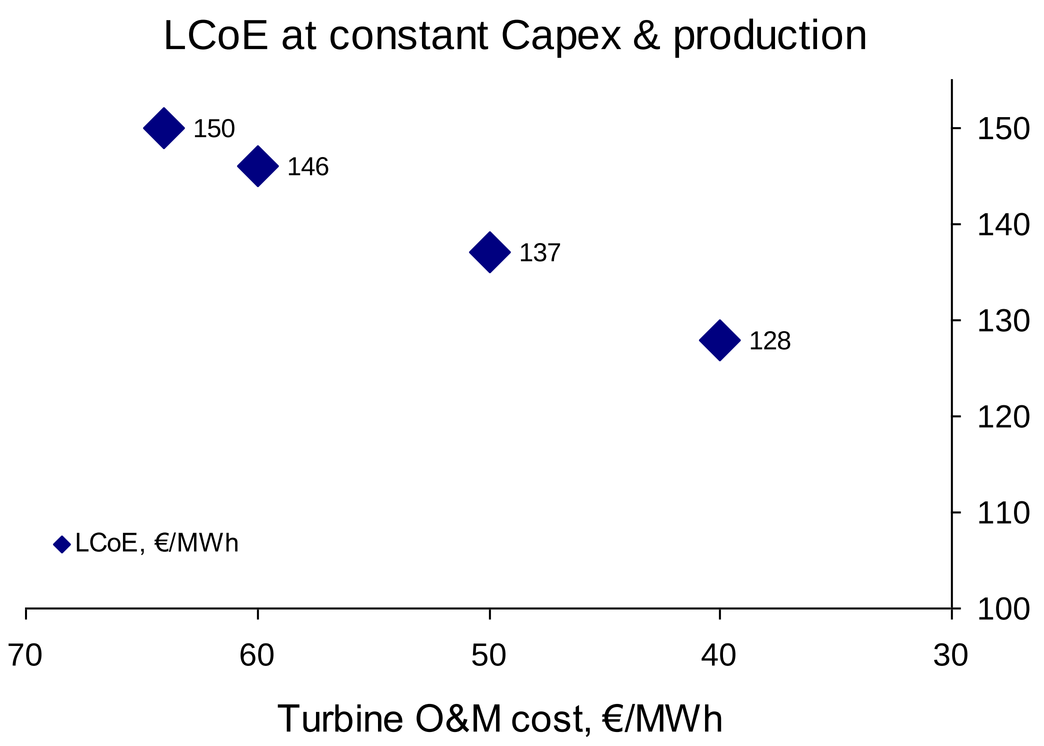




## Output screen

- This case has total Capex €3.3m / MW
- Model allows ”free” parameter variation
- Graphic breakdown of each cost category

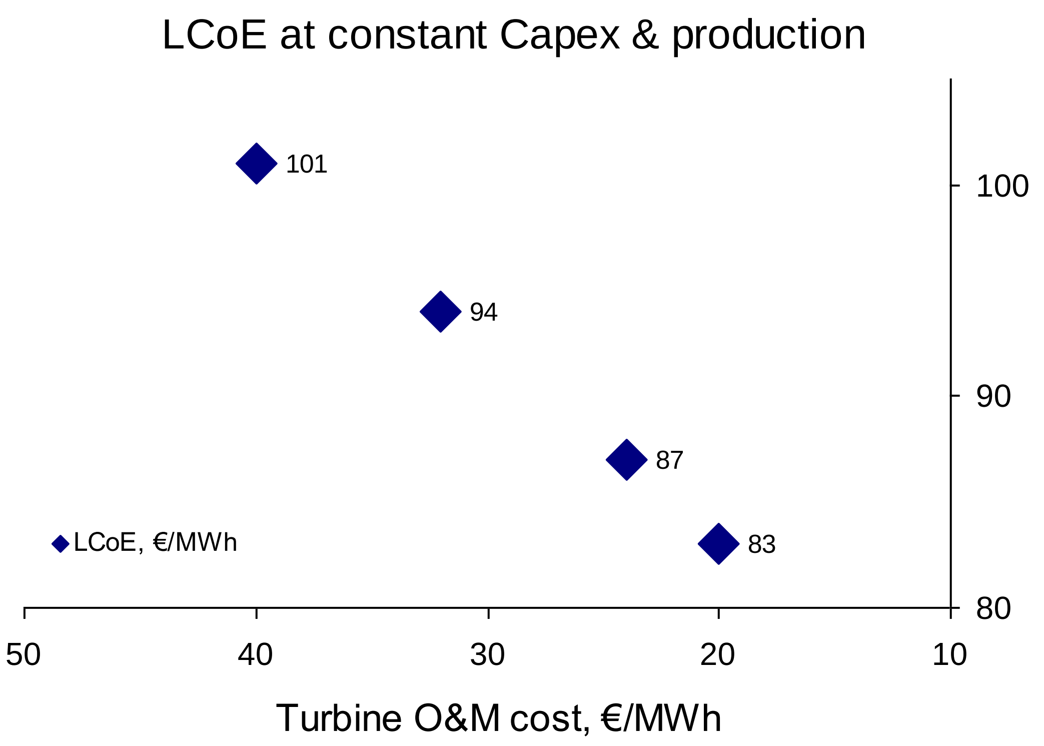
# Example results 1: O&M cost can have major influence on LCoE

## Arrays and early stage farms (to 2030)




| | |
|---|---|
| WACC | 6% p.a. |
| Total Capex | €3.3m/MW |
| Turbine Capex | €2.0m/MW |

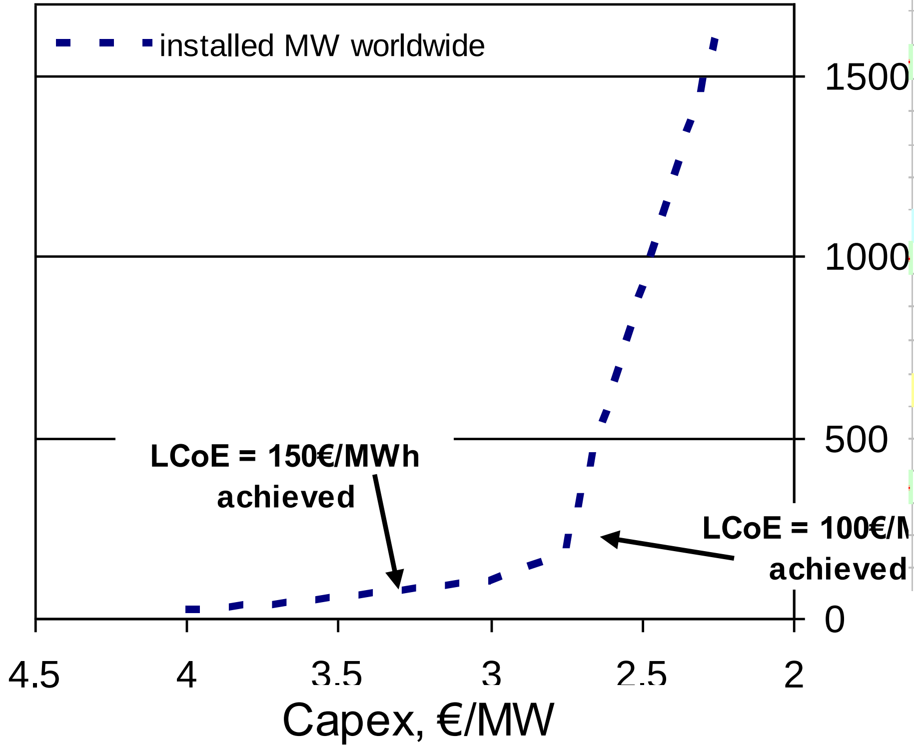
## Commercial tidal farms (2030's)




| | |
|---|---|
| WACC | 5% p.a. |
| Total Capex | €2.7m/MW |
| Turbine Capex | €1.5m/MW |

# Example results 2: Influence of cost reduction on market take-off

## Market-evolution model snapshot, example output




| RealTide Market Evolution Model | | GLOBAL SCENARIO FOR TIDAL-STREAM POWER | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2021 July version | | | | | | | | | | | | |
| | | | Tidal Arrays Validation Phase | | | | | Deployment Decades | | | | |
| FLH/year assuming 40%: | 3500 | | | | | | | 2030's: Growth | | 2040's: Consolidation | | Matur |
| | | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031-35 | 2036-40 | 2041-45 | 2046-2050 | 2051-55 |
| | | | annual averages | | | | | averages over each 5-year period | | | | |
| TWh produced | p.a. | 0.025 | 0.035 | 0.080 | 0.150 | 0.320 | 0.600 | 5.78 | 20.0 | 42 | 70 | 105 |
| GW installed | cumulative | 0.01 | 0.020 | 0.033 | 0.053 | 0.101 | 0.181 | 1.660 | 5.724 | 12.0 | 20.0 | 30.0 |
| new capacity added in period, MW | | | 10 | 13 | 20 | 49 | 80 | 1479 | 4064 | 6286 | 8000 | 10000 |
| - over # years in period | | | 1 | 1 | 1 | 1 | 1 | 5 | 5 | 5 | 5 | 5 |
| - annual new capacity | MW/a | | 10 | 13 | 20 | 49 | 80 | 296 | 813 | 1257 | 1600 | 2000 |
| capex, new tidal stream | €/kW | 4,500 | 4,000 | 3,750 | 3,500 | 3,000 | 2,750 | 2,250 | 2,100 | 2,000 | 1,900 | 1,800 |
| *Reference capex, Floating Wind *** | | *3,000* | | *3,000* | *2,750* | | *2,250* | | *1,825* | | *1,650* | |
| *cost premium TC over offshore wind (see NB note)* | | *50%* | | | *27%* | | *22%* | | *15%* | | *15%* | |
| annual capex on TC power | €m/a | | 40 | 48 | 70 | 146 | 220 | 665 | 1707 | 2514 | 3040 | 3600 |
| cum. investments TC power | €m | | 40 | 88 | 158 | 304 | 524 | 3,851 | 12,386 | 24,957 | 40,157 | 58,157 |
| # machines installed per year**** | | <5 | 10 | 13 | 20 | 32 | 40 | 99 | 271 | 314 | 400 | 333 |
| - average power/machine | MW | 1 | 1.0 | 1.0 | 1.0 | 1.5 | 2.0 | 3.0 | 3.0 | 4.0 | 4.0 | 6.0 |
| # MW-scale machines operational | | 10 | 20 | 33 | 53 | 85 | 125 | 618 | 1,973 | 3,544 | 5,544 | 7,211 |
| - avg. power, all installed | MW | 1 | 1.0 | 1.0 | 1.0 | 1.1 | 1.4 | 2.7 | 2.90 | 3.39 | 3.61 | 4.16 |
| **TCT-blade segment (Prime Mover)** | | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | by 2035 | by 2040 | 2045 | 2050 | 2050's |
| #blades sold per year | | <15 | 25 | 32 | 50 | 81 | 100 | 246 | 677 | 786 | 1,000 | 833 |
| capex share on blades | | >20% | 20% | 20% | 20% | 20% | 15% | 12.5% | 12.5% | 10% | 10% | 10% |
| capex amount on blades | €/kW | >1000 | 800 | 750 | 700 | 600 | 413 | 281 | 263 | 200 | 190 | 180 |
| **Tidal blade market size** | **€m/a** | <2 | 8.0 | 9.6 | 14.0 | 29.1 | 33.0 | 83.2 | 213 | 251 | 304 | 360 |

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# Operation and Maintenance (O&M) Model

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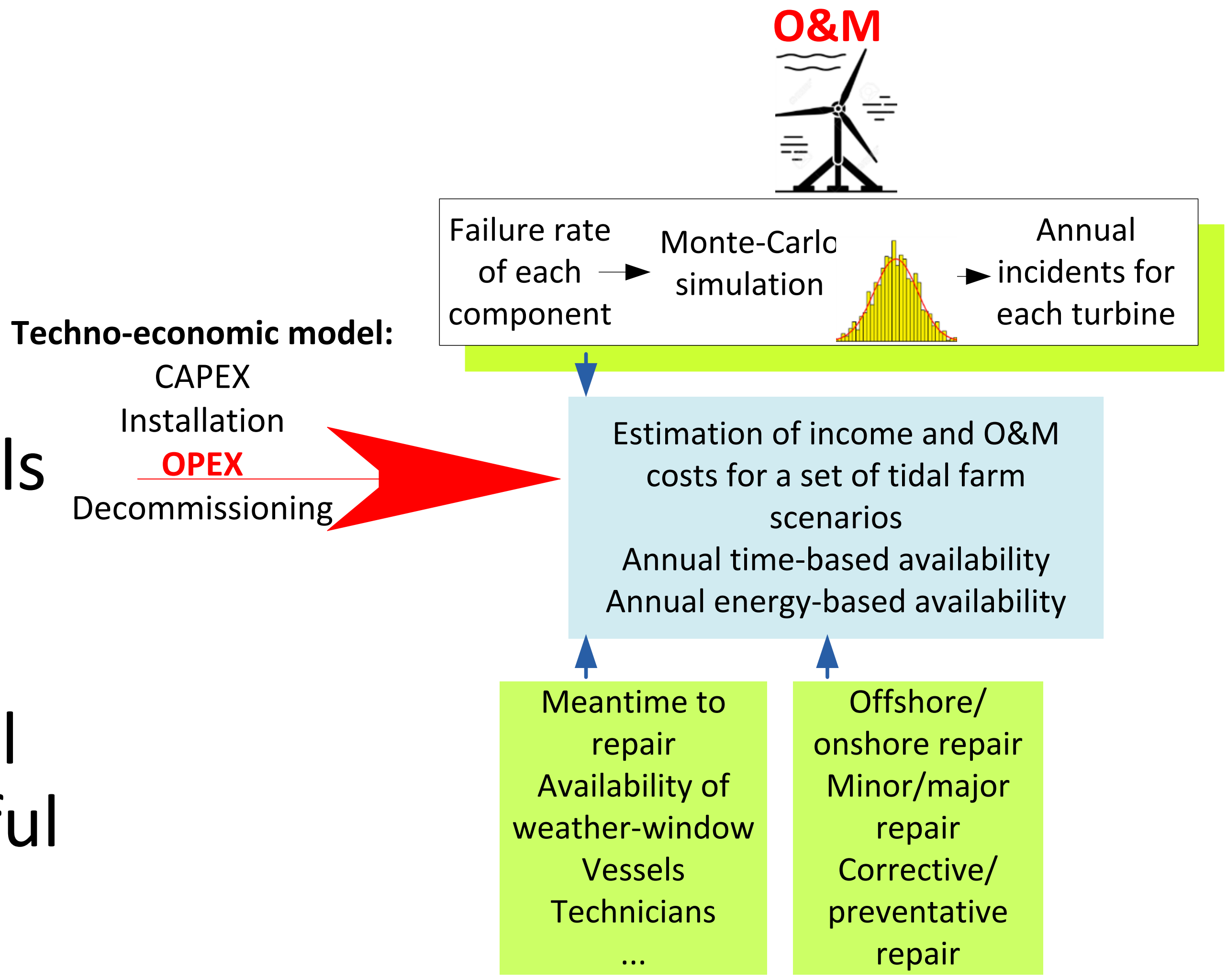
# Impact of O&M model

- The O&M model is useful for the assessment of tidal turbines' maintenance strategies and their costs.
- The model runs scenarios and details annual numbers of fails, downtime hours and energy, vessel costs, etc.
- These quantify the reliability of tidal turbines at all stages which are useful for the asset owners, device designers and developers.



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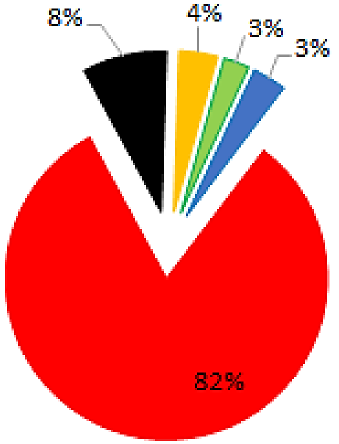
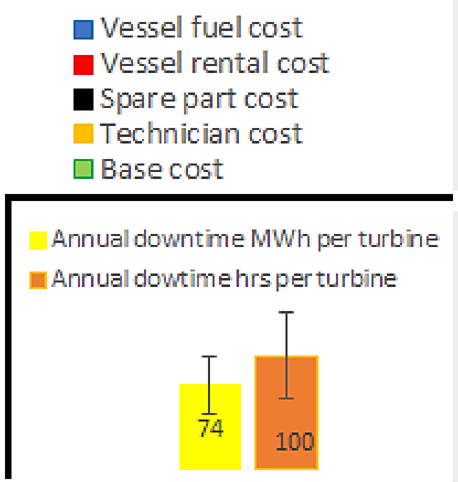
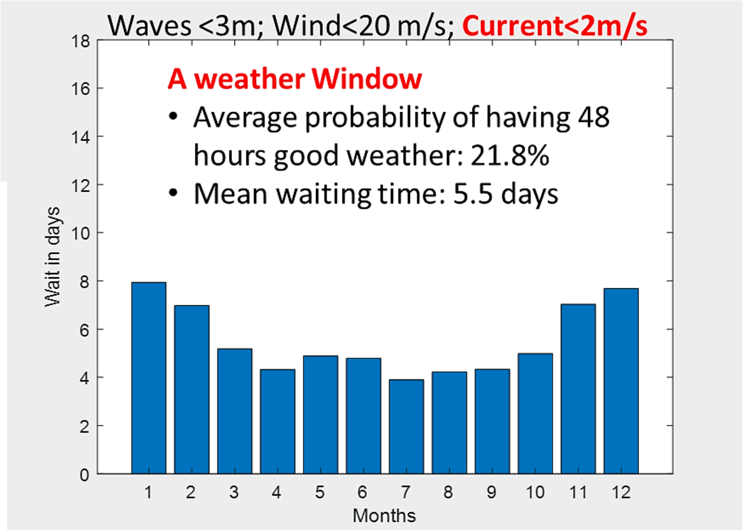
# Outputs & lessons learned

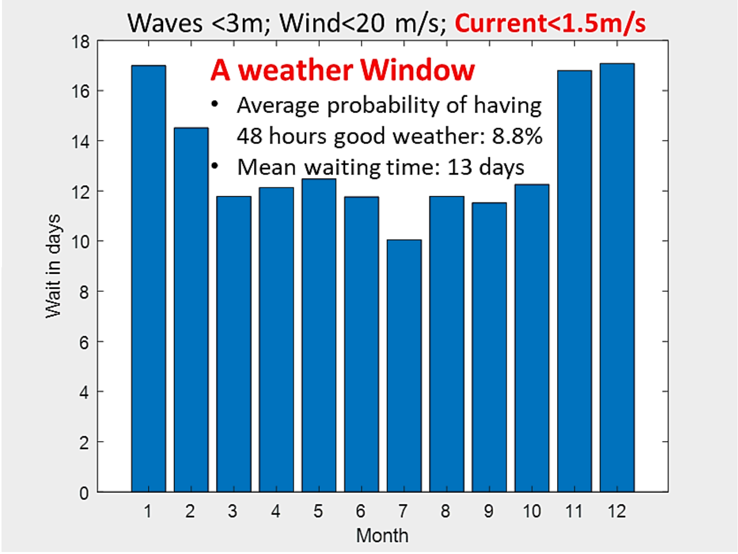
- An iterative approach to the O&M analysis can inform the decisions about the direction for reliability improvements.
- Weather window limits should consider a max wave height but also wave period, wind speed and current speed.

Example: Annual mean of O&M cost breakdown for a projected tidal farm of 50 turbines (0.5 mean fail per turbine)



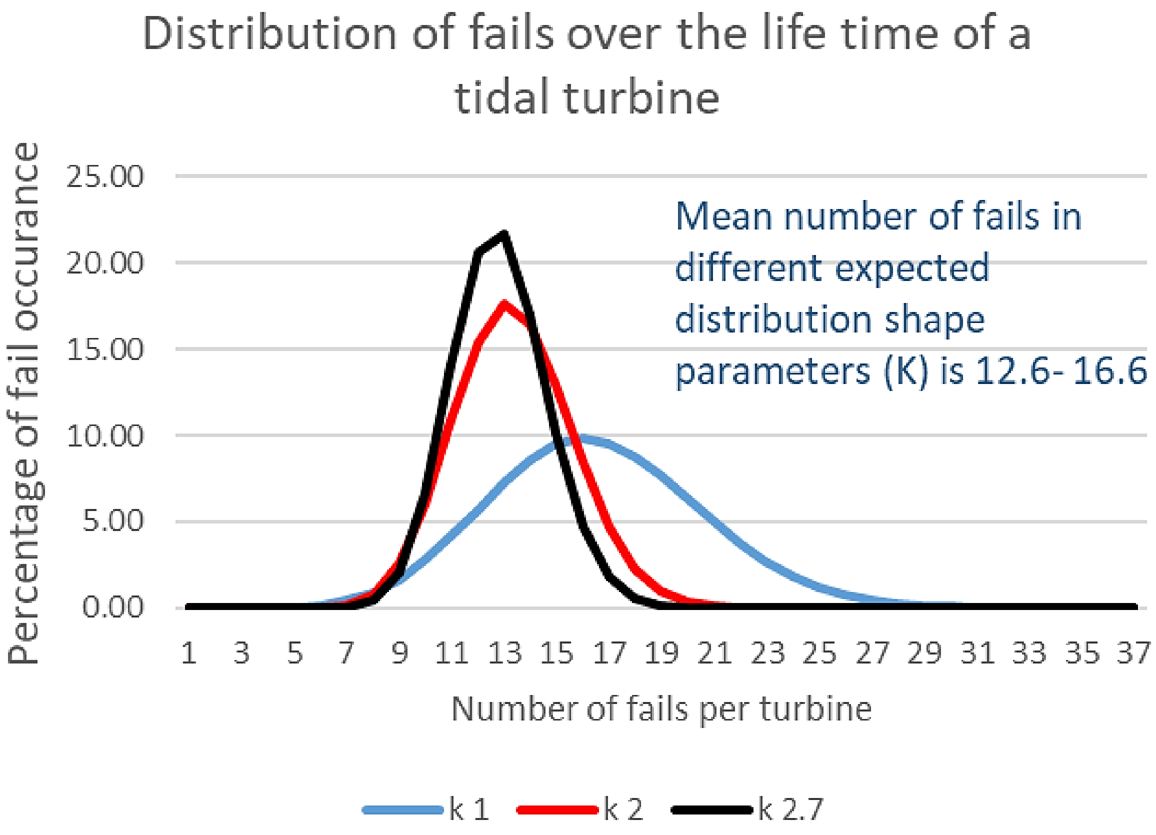



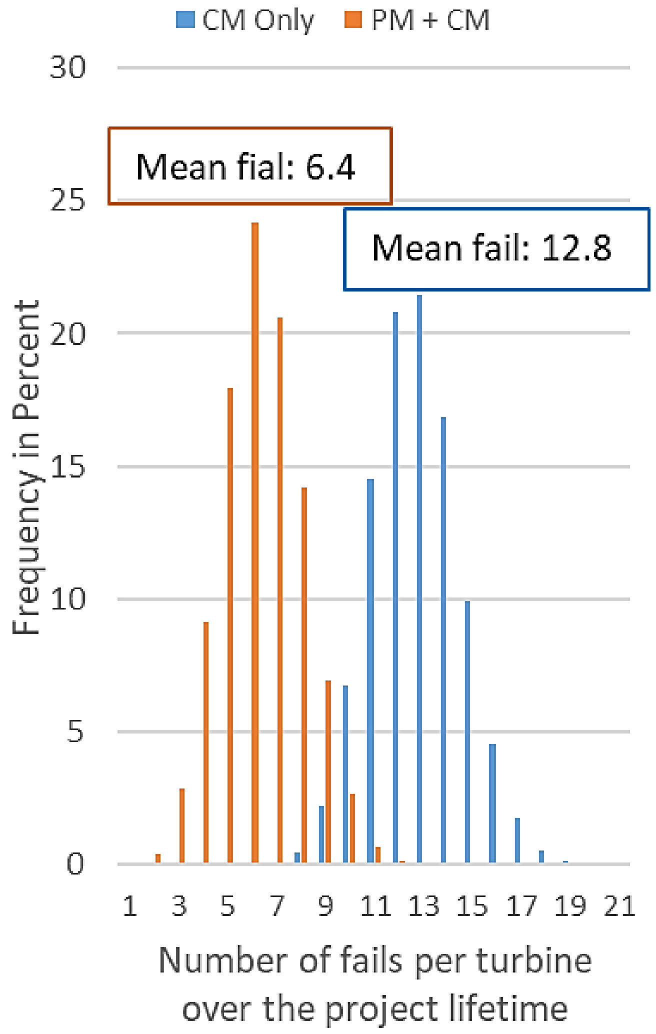
# Research highlight

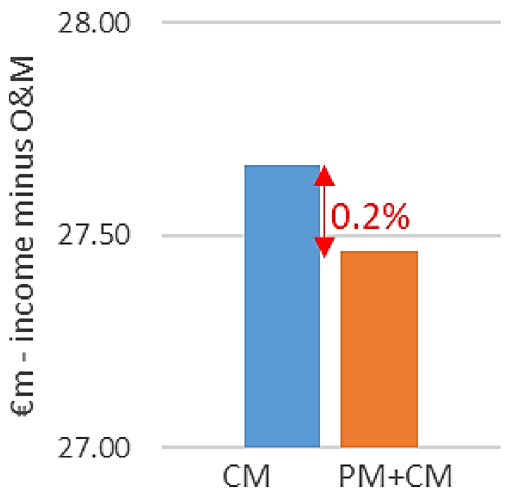
- Decreasing the uncertainty in the number of fails a turbine experiences in its life, assists decision making about the turbine maintenance strategy.
- This will increase the accuracy of the forecasting of the cost of energy for tidal turbines.



# Research highlight

- Compared to only corrective maintenance (CM), preventative maintenance (PM) decreases the number of turbine fails by 50% in the example
- But PM+CM decreases the uncertainties/risk in project.



# Further information

- Alpha version of the model is to be published in MONITOR Deliverables
- For this presentation, a paper is under preparation
- Contact: mitra.kamidelivand@ucc.ie

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This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 727689

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# Standardisation

Stéphane Paboeuf
Bureau Veritas Marine & Offshore

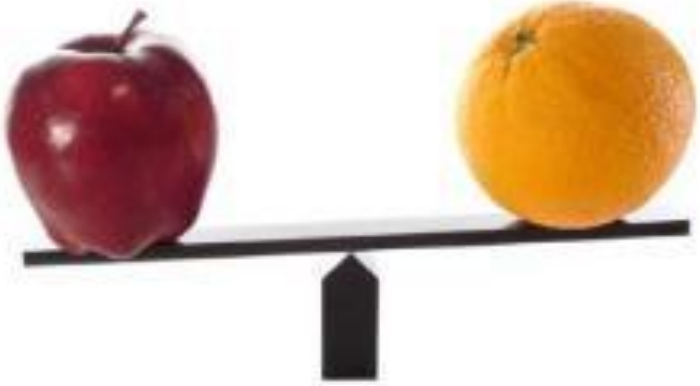
# Why asking for standardisation?

- Quality

- Safety

- Reliability

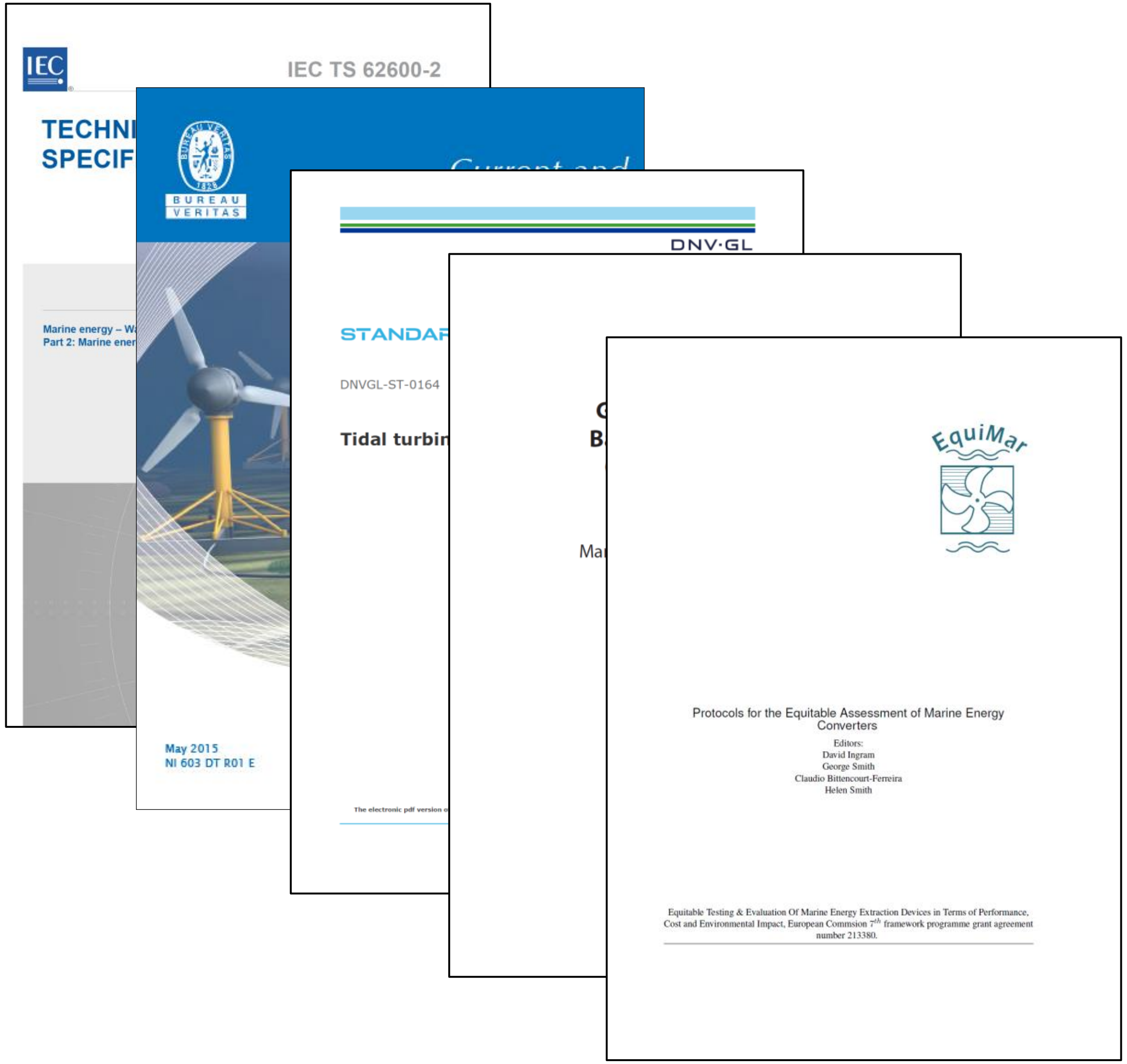
- Comparison



Give confidence to insurers, bankers, investors, owners, end users,….

# Existing standards

- IEC TC114 – IEC 62600 series
  Marine energy - Wave, tidal and other water current converters
  - Design requirements
  - Mooring system
  - Electrical power quality
  - Acoustic characterization
  - Resource assessment and characterization
  - Power performance assessment
  - Testing
- DNVGL-ST-0164, DNVGL-SE-0163
- BV NI603, NI631
- EMEC Guidelines
- EQUIMAR Protocols



# IEC Standards

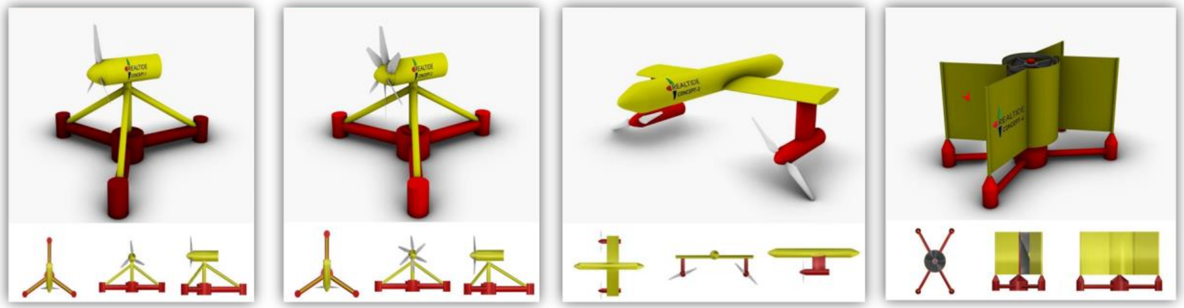

IEC

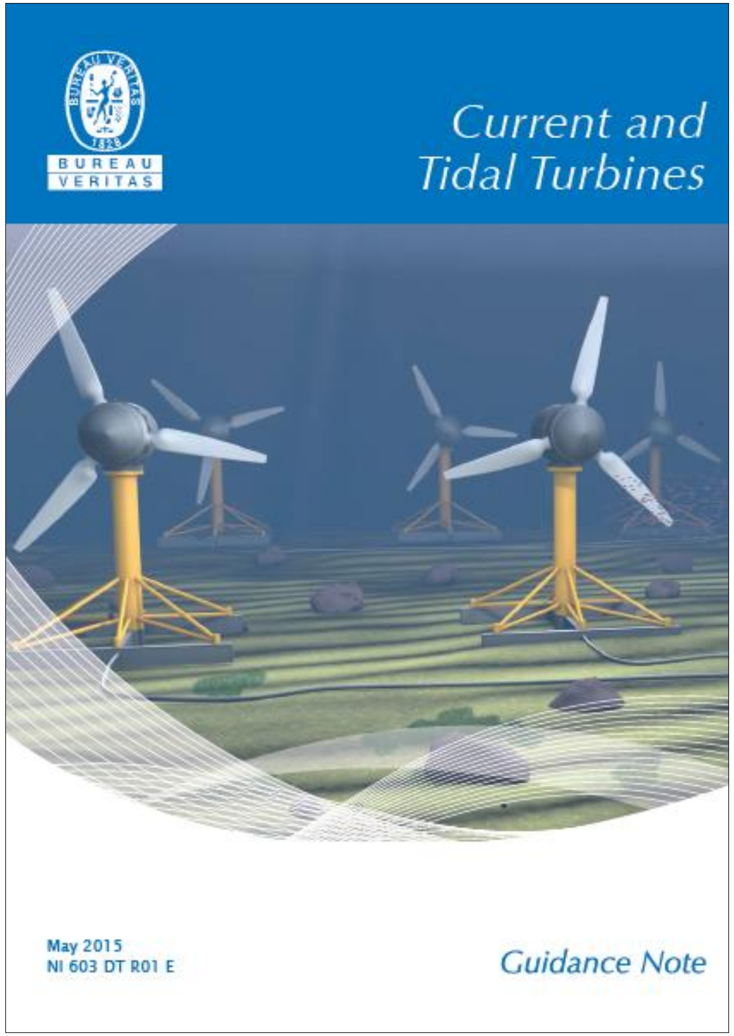
- **MT 62600-200** is currently preparing the 2nd edition of the tidal power performance assessment TS
- **MT 62600-201** is currently revising the 2nd edition of the tidal resource assessment and characterisation
- **PT 62600-202** has been commented
- **TS 62600-2** was published in November 2019, **TS 62600-3** in May 2020 and **TS 62600-30** in August 2018, none are currently being revised.

# Bureau Veritas NI603

- Fatigue methodology for blade made in composite materials (WP1),
- Reliability database access (WP1),
- Condition monitoring protocol (WP4),
- Testing procedures (WP4),
- Calculation methods: analytical (BEMT) and numerical (CFD) (WP3 and WP5).

Concept 1 - Complex bottom fixed | Concept 2 - Simple bottom fixed | Concept 3 - Floating multi rotor | Concept 4 - Crossflow tidal turbine





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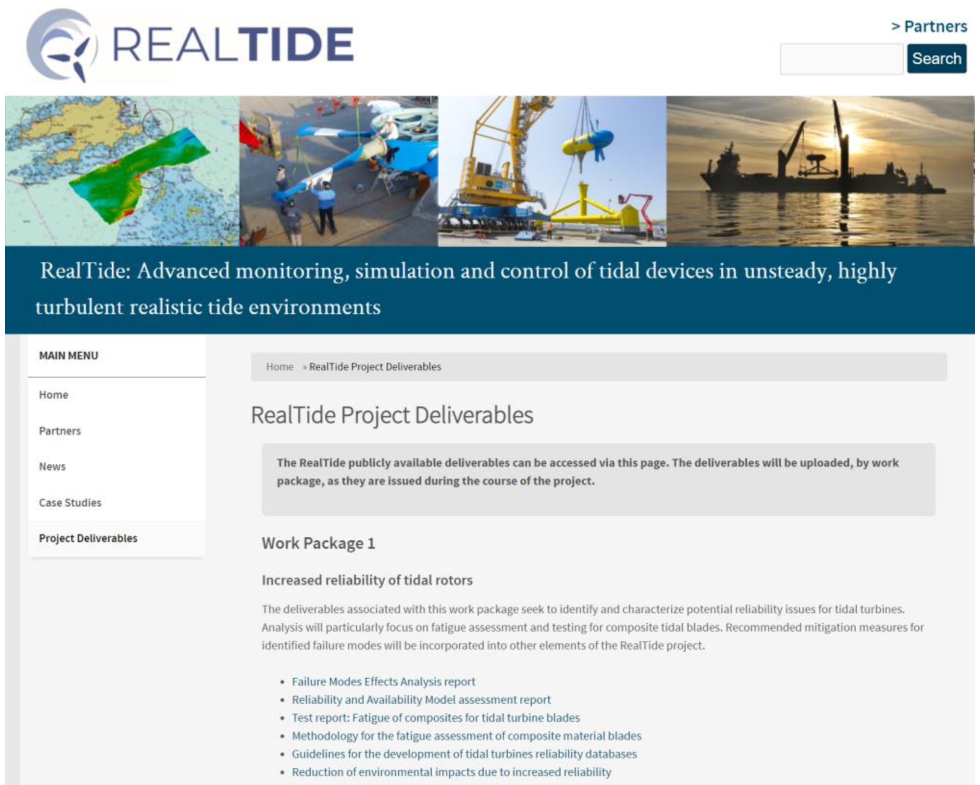
# Public documents

- Public reports

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- Scientific Publications

| Type | Title | Authors | Title of the Journal/Proc./Book |
|---|---|---|---|
| Poster | Keys to taming the cruel sea: Critical enabling steps towards commercial exploitation of unsteady flow, highly turbulent real tide environments | O. Benyessad, N. Larivière-Gillet, D. Ingram, B. Sellar, P. Mayorga, P. Salazar, E. Nicolas, … | ICOE2018 |
| Conference | Reliability of Composite Tidal Turbine Blades | M. Arhant, Peter Davies, S. Paboeuf, and E. Nicolas | ICCM22 |
| Conference | Improving reliability of tidal turbines: a new step by step methodology for initial quantification of criticality and recommendations | Vincent P. LE Diagon, Pedro M. Mayorga, Ana I. Mayorga, Ningxiang Li, … | EWTEC2019 |
| Conference | Tide-to-wire Model Development for Realistic Tide Environments | Joseph Praful Tomy, Marios C. Sousounis, Stéphane Paboeuf, and Jonathan K. H. Shek | EWTEC2019 |
| Conference | Currents, wave and turbulence measurements: a view from multiple industrial-academic projects in tidal stream energy | M. Dorward, B. Sellar; C. Old; P. R. Thies | IEEE-OES |
| Conference | Implications of asymmetric beam geometry for convergent acoustic Doppler profilers | Harding S, M. Dorward, B. Sellar, M. Richmond | IEEE-OES |
| Journal | Dynamic, Fully Coupled, Electro-mechanical Models of Tidal Turbines | Arturo Ortega; Joseph Praful Tomy; Jonathan Shek; Stephane Paboeuf; David Ingram | Journal Energies |
| Journal | Field validation of an actuated convergent-beam acoustic Doppler profiler for high resolution flow mapping | S. Harding, M. Dorward, B. Sellar, M. Richmond | Journal of Measurement |
| Journal | Single-beam acoustic Doppler profiler and co-located acoustic Doppler velocimeter flow velocity data | M Jourdain de Thieulloy, M Dorward, C Old, R Gabl, T Davey, DM Ingram,B. Sellar | Journal Data |
| Journal | On the use of a single beam acoustic current profiler for multi-point velocity measurement in a wave and current basin | M Jourdain de Thieulloy, M Dorward, C Old, R Gabl, T Davey, DM Ingram, B. Sellar | Journal Sensors |
| Conference | Application of ply-by-ply fatigue analysis methodology in the design of a full-scale tidal turbine blade | Joseph P. Tomy, Luc Mouton, Stéphane Paboeuf, Mael Arhant, … | EWTEC2021 |
| Conference | Material and structural testing to improve composite tidal turbine blade reliability | P. Davies, M. Arhant, N. Dumergue, E. Nicolas, S. Paboeuf, P. Mayorga | EWTEC2021 |
| Conference | Experimental assessment of the loads to which tidal turbines are subjected using conditions derives from field measurements | D. Ingram et al. | EWTEC2021 |
| Conference | Increased Reliability of tidal turbines thanks to a better knowledge of realistic tidal conditions, use of RAM analysis, advanced monitoring, maintenance strategies and intelligent design components | Vincent LE DIAGON, Pedro Mayorga, Manunnggal Sukendro, Ningxiang Li, … | EWTEC2021 |

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# Reality bites: the challenge of adapting your device in a real site

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# Tidal turbine environment

- **Operation in harsh environment:**
  - high currents,
  - waves
  - unsteady flow,
  - fouling, abrasion….
- **Installed on seabed:**
  - no internal inspection possible, supervision by sensors,
  - no on-site repairs.
- **Specific conditions for each site:**
  - Current velocity, wave high, turbulence intensity → power production, extreme loads, fatigue loads
  - Bathymetry → size of rotor
  - Water temperature → cooling, type of fouling

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# lessons learned

- A minor failure can require the turbine to be retrieved and repaired onshore;

- The turbine retrieval requires an expensive offshore operation with a DP vessel with a high crane capacity;

- Few weather windows for offshore operations (during neap tide, with good waves conditions): risk of long downtime for maintenance.

**Reliability represents a key factor in the tidal turbine business model,** particularly for OPEX (limiting maintenance operations) and revenues (reducing downtime).

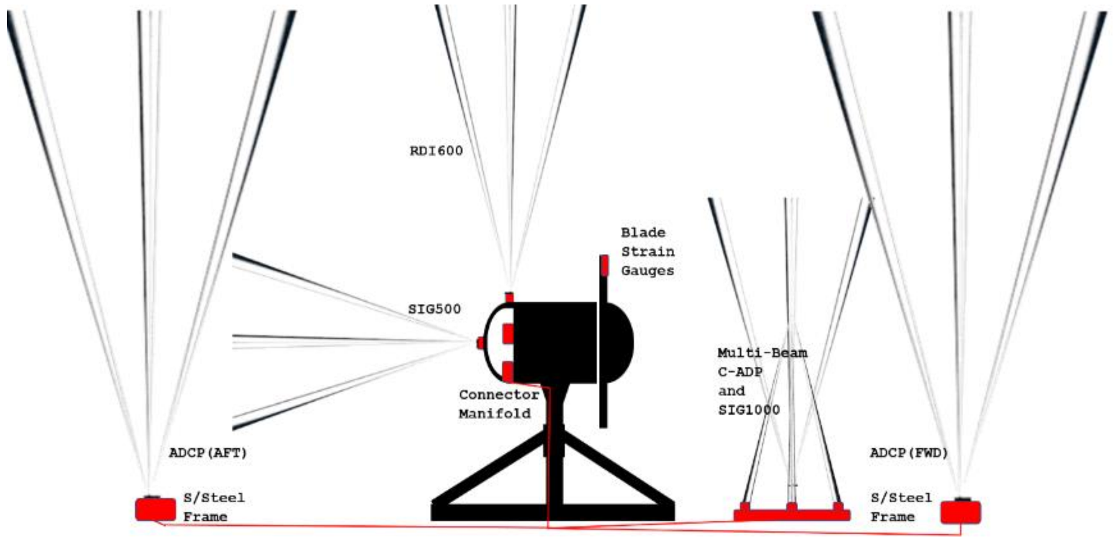
# Reliability assesment

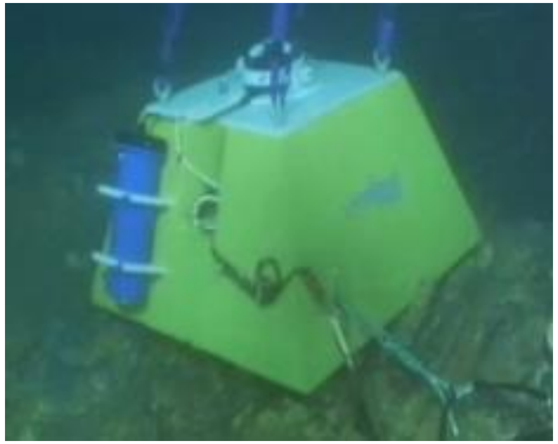
- FMEA → Define a list of equipment failure modes with effects on tidal operation,
- RAM assessment → Define global system reliability and identify critical components to improve design and/or monitoring
- VMEA → Understand the influence of uncertainties on components designed for a specific site (blades)

| Sub-system | Assembly | RAM Component | Failure rate (/year) | MTTR (Hours) | | | Production Impact |
|---|---|---|---|---|---|---|---|
| | | | | Major | Minor | Trivial | |
| Hydrodynamic System | Nacelle | **Nacelle Body** | 1.13% | 1.69% | 0.14% | 0.01% | 100% |
| | Rotor | **Blades** | 8.50% | 1.69% | 0.18% | 0.02% | 100% |
| | | **Pitch System** | 17.07% | 1.21% | 0.16% | 0.01% | 100% |
| | Yaw system | **Yaw system** | 11.33% | 1.69% | 0.13% | 0.01% | 50% |

# adapting to the environment

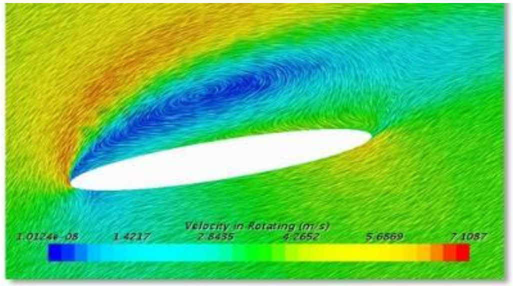
- Each site is different, need a high level of flow characterisation to adapt design and control of turbines
  - ➢ Adapt blade design to maximise power capture
  - ➢ Characterise the influence of unsteady flow on power variation and on load fluctuation
  - ➢ Refine mission profile for fatigue assessment (foundation, blades)

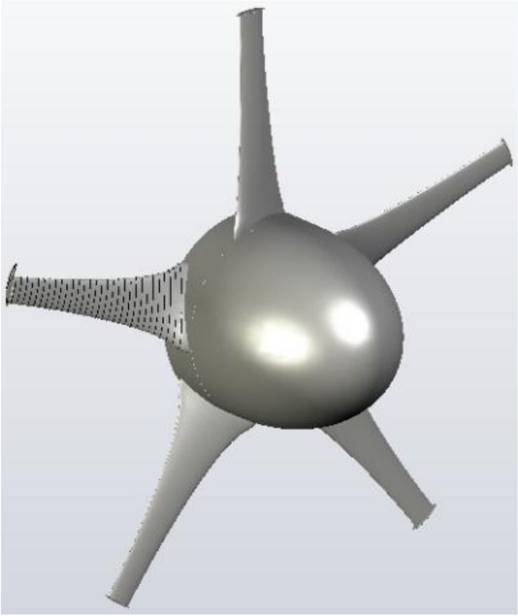


# Modelling

- BEMt → preliminary rotor design
- Tide to wire model → optimisation of turbine control for the site, mission profile for electrical conversion components
- LCoE model → economical viability of the solution, design to cost
- CFD → blade design optimisation, pressure field for structural design





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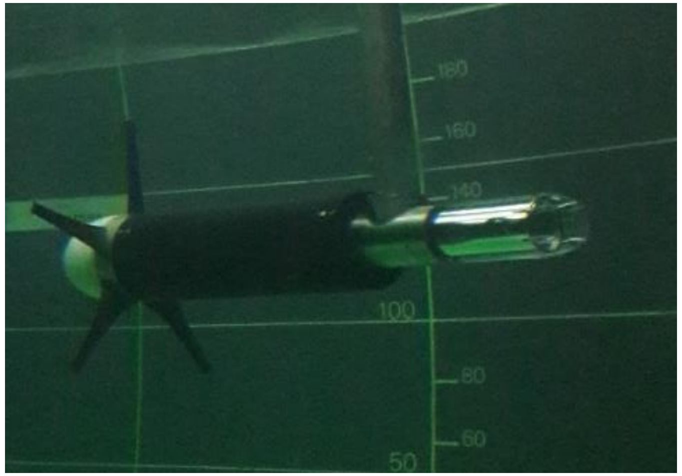
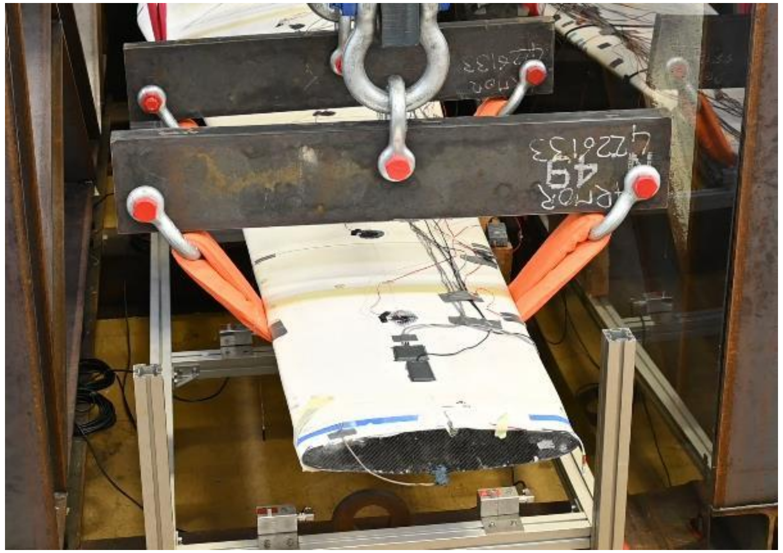
# Lab testing

- Tank testing → check the rotor characteristic (Performance, thrust, TSR), define influence of current + waves + turbulences on blade loads
- Prototype blade test → check the blade behaviour with static and fatigue loads to validate the structural design

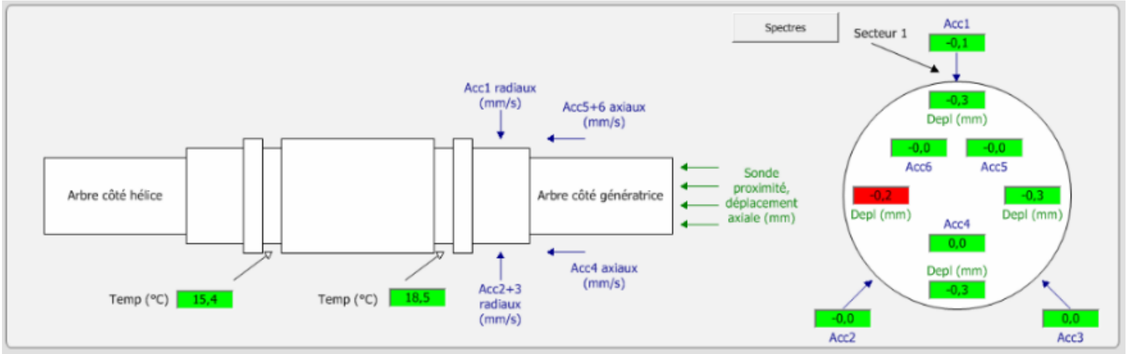


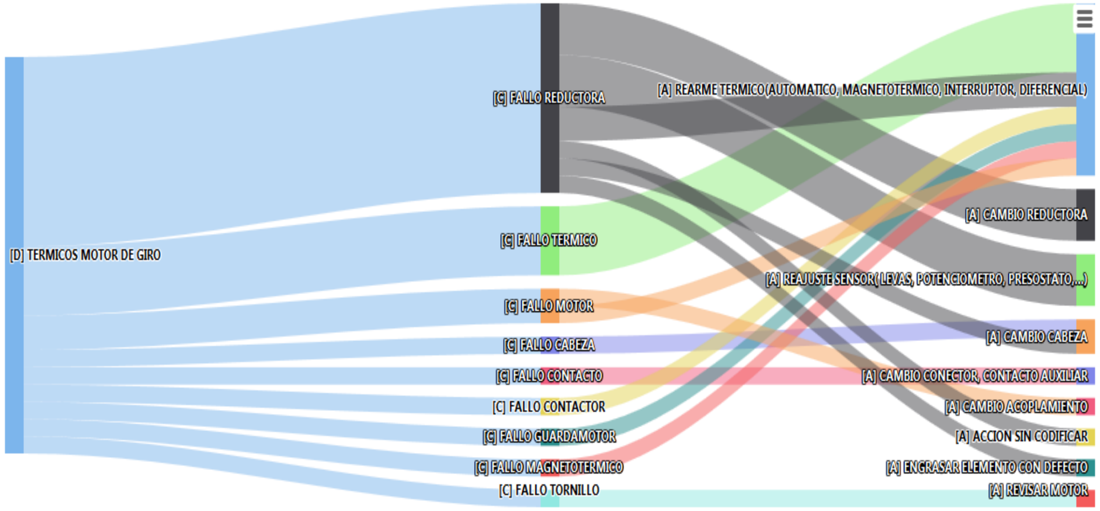


# Monitoring

- Define an adapted monitoring technique to measure the critical parameter on each critical component
- Develop a SCADA analysis to detect failure by measuring variation on monitored parameters

➢Detection of failure before it occurs, avoid unexpected maintenances and prepare preventive maintenance



# Part 4

Panel Discussion and Questions – 15mins