



EnFAIT



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ENFAIT ENABLING FUTURE ARRAYS IN TIDAL

D9.7 – Best Practice Report on Intra-array Layout and Control



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I Introduction

1.1 The Project

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme in January 2017 to demonstrate a grid-connected tidal energy array at a real-world tidal energy site, propelling tidal energy towards competing on a commercial basis with alternative renewable sources of energy generation – Enabling Future Arrays in Tidal (EnFAIT). This was in response to the call *LCE-15-2016: Scaling up in the ocean energy sector to arrays* to generate significant learning through demonstration of cost-effective tidal arrays.

1.2 Scope

This deliverable “D9.7 Best practice report on intra-array layout and control” discusses the design and operation of the electrical infrastructure and control systems for arrays of tidal stream turbines.

To reliably produce good quality electrical power from an ever-changing marine environment requires precise control of the turbines. This requires knowledge and modelling of the individual components and subsystems within the turbines. On a larger scale, the intra-array electrical network connects the individual turbines in the array and delivers the power to shore. It also sends control signals to the turbines. The design of the intra-array electrical network depends on many factors, some of which are summarised in section 3, but are beyond the scope of this report to cover in detail.

There is not yet an agreed standard on how best to design and operate the intra-array cables and turbine control system. This is particularly the case for controlling multiple turbines together. Indeed there may be quite different approaches adopted for different situations, deployment sites, or device concepts. This report therefore presents the findings and knowledge of the EnFAIT project partners in order to further develop the sector. This does however need to consider commercial sensitivities. It must also account for the current state of the sector, i.e. the first pre-commercial arrays have been built and operating for several years, and several companies are now planning and developing early commercial arrays.

1.3 Different scales/approaches to modelling

Many different models are used to inform the design of arrays and individual turbines, subsystems, and components. In these, there is an inherent trade-off between complexity and accuracy. We typically want to keep things as simple as possible but include enough complexity to describe the problem accurately enough.

"All models are wrong, some are useful"

— George Box, statistician

The scope and detail of these models should also be considered, with a broader scope tending towards lower detail of individual processes modelled.

- On one hand, we can consider the details of individual components: using models of how these behave. For example, detailed computer fluid dynamics (CFD) modelling of the water flow over a turbine blade.
- On the other, when modelling at an array scale, turbine rotors are often represented as a series of actuator discs rather than resolving individual blades. This significantly reduces the computational expense.

The level of detail considered within a model also affects the amount of detail required in the input data; again, increasing the effort to build and run these models.

Different approaches of modelling could be grouped, as shown schematically in Figure 1-1, into:

- 1) Simple calculations with a limited scope and detail.
- 2) Detailed component or subsystem models, taking a bottom-up approach to accurately represent these items with a high degree of accuracy, but a limited scope to keep computation and input data reasonable. As the design of a component or subsystem evolves, this can be represented more accurately within the model.
- 3) Holistic/top-down models considering the whole array, but with a trade-off of reducing the complexity of modelling for each subsystem/parameter of interest. This is especially true for early-stage design, where detailed input data may not be available, or a wide range of the parameter space should be investigated.

Approaches 2) and 3) are discussed separately in the following chapters.

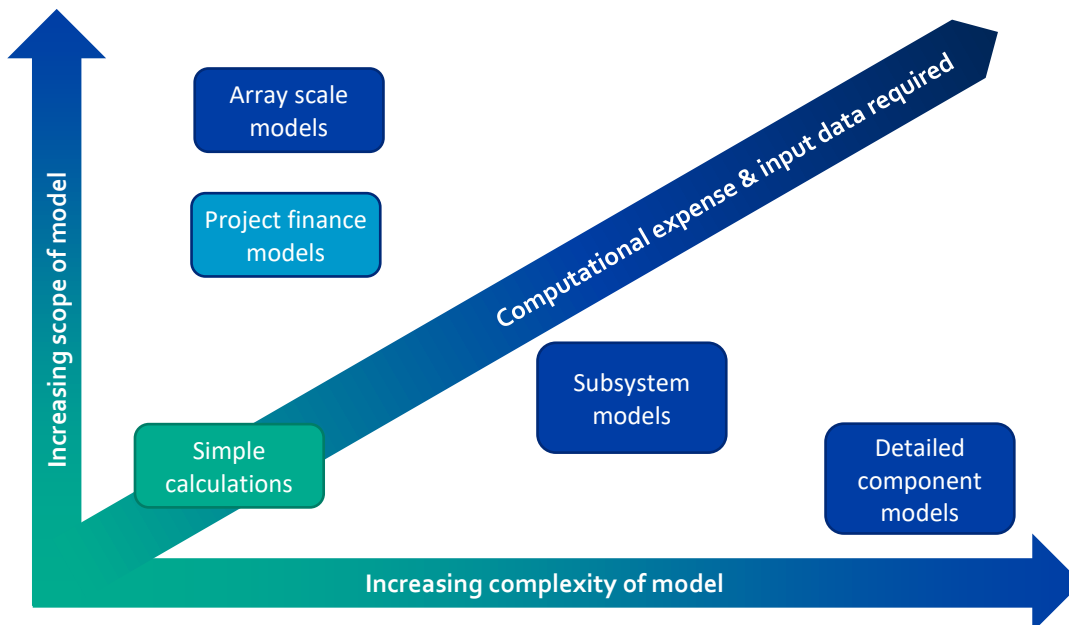
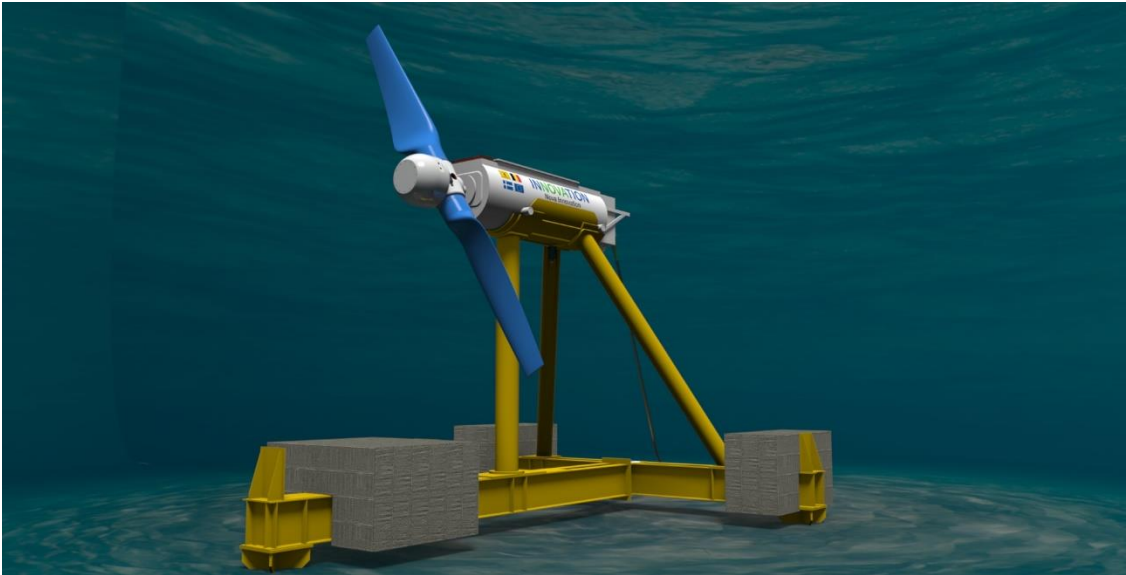


Figure 1-1. Schematic showing trade-off between complexity, scope, and computational expense and input data requirements

2 Turbine Design

This document will not go into details of specific electrical architectures, here only discussing aspects that relate substantially to intra-array electrical architectures. The main electrical powertrain systems typically used in turbines leading the market today are a generator, converters (drives), connector(s), switchgear/circuit breaker(s), cable, and transformer(s). Lower voltage systems will include electrically actuated or controlled systems such as brakes, pitch, or yaw systems, as well as control and monitoring systems.



From an array control perspective, the resulting architectures can be split into the following main groups:

- Onboard control – all the required components to control the device are inside the turbine, with fixed frequency and common voltage electricity leaving the turbine.
- Off-turbine control (single turbine) – A turbine with drives remote from the turbine which operates independently of any other turbines.
- Off-turbine control (shared) – turbines sharing some subsystems of the power regulation system, where the control of multiple turbines is tied together (e.g. shared power conversion drives).

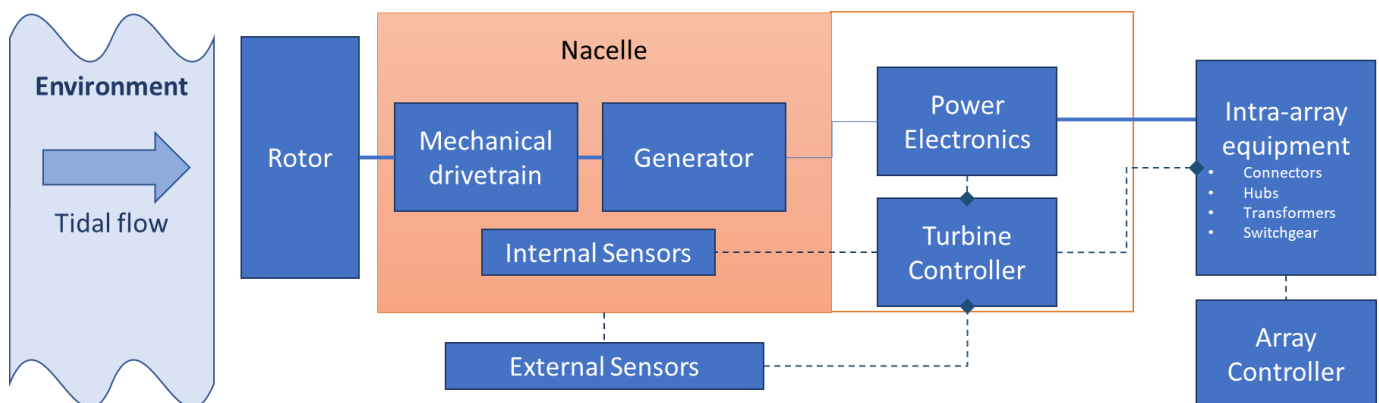


Figure 2-1: Example turbine layout showing onboard control. For off-turbine control the power electronics (converter) and turbine controller may be part of the intra-array equipment

As can be seen in Figure 2-1, the main subsystems of the turbine are the rotor, comprising of the hub and blades; mechanical drivetrain and smaller subsystems such as brakes; the generator, which can either be direct drive or gearbox driven; and the electrical conversion and control equipment, which may be inside the turbine or elsewhere in the array.

For each of the subsystems, choices are made in the design phase in order to achieve the best reliability and availability, resulting in the lowest cost of electricity generation.

Table 2.1 gives examples of different considerations when designing a tidal turbine and turbine array.

Table 2.1. Summary of interlinking and often conflicting parameters influencing turbine design (non-exhaustive)

Theme	Parameters/notes/examples
High level design choices	<ul style="list-style-type: none"> Physical size of turbine and blades, rated power, cut-in cut-out velocities Whether on a floating platform or fixed to a structure or seabed...
Power regulation	<ul style="list-style-type: none"> Method of regulation during normal operation (stall, pitch etc.) Back-up regulation (mechanical or electrical braking, energy storage, safety systems etc.)
Turbine high level control	<ul style="list-style-type: none"> Self-sufficient (on-board) or remote Individual turbine or linked Communication method with array
Drivetrain	<ul style="list-style-type: none"> Geared system easily scalable across size ranges often using standard parts Direct drive system very low maintenance, but heavier than geared drivetrain. Often bespoke design
Generator	<ul style="list-style-type: none"> Induction or permanent magnet, winding design etc. Voltage range
Power electronics (convertors)	<ul style="list-style-type: none"> Cost effective availability at a suitable voltage and power Required level of control capability, and level of functionality within proposed architecture Export Voltage Operational environment and reliability- vibration, salinity, cooling options Space envelope
Connectors (electrical)	<ul style="list-style-type: none"> Cost effective availability at a suitable voltage and power Wet or dry mate, or semi-permanent connections Compatibility with structural connection method Compatibility with array communication method Marine operations requirements
Cable	<ul style="list-style-type: none"> Distance to substation/hub Flow, seabed conditions Management from turbine to seabed (floating systems in particular) Marine operations requirements
Transformers	<ul style="list-style-type: none"> Requirement driven by components above
Reliability and maintenance interval	<ul style="list-style-type: none"> Strategic choice of components to ensure all subsystems accessed during the same maintenance operation have similar maintenance intervals Easy accessibility of inherently low reliability/short maintenance interval parts
Environmental/social factors	<ul style="list-style-type: none"> High level choices will often be driven by these factors, e.g. floating systems not permitted in shipping lanes, large onshore substations not popular in areas of natural beauty, etc. Very important to consider, but beyond the scope of this report.

2.1 Turbine operation and control

2.1.1 Power regulation

As discussed above, the physical position of the key electrical components can substantially change how the turbine is controlled.

Convertors suitable for controlling relatively low inertia systems such as tidal turbines typically use encoders to provide feedback of the generator control, these requiring close physical proximity. Encoder-less control is also possible but has its own limitations. The distance between converter and turbine is limited by the converter capabilities and the effect of other components such as transformers. A transformer capable of handling variable frequency may be required between converter and turbine to minimise losses.

Nova Innovation have to date always produced stall-regulated turbines, where all power regulation control is carried out through the converter. Where turbines have other methods of control such as pitch systems, should these systems respond quickly enough, further options for off-turbine power conversion may be realised at the expense of more complex onboard systems.

The generator itself can affect control options too, with high speed (geared) induction generators resulting in a higher inertia system with some slip, and direct drive permanent magnet systems being much more rigid and low inertia.

Conversion equipment needs to be certified for use in the country the turbine is to be operated. Use of appropriate type certified equipment makes compliance to the local electrical regulations much more straight forward. For a generation station (turbine or array) there is usually a demand from the DNO (Distribution Network Operator) for an amount of voltage control to help stabilise the grid. The DNO will also usually require a certain amount of fault ride through i.e., where the generation plant will not trip out on a short network outage. The DNO may have additional requirements; generally, no two DNOs have the same requirements. Such criteria need to be considered when designing the architecture of the power conversion equipment.

2.1.2 Turbine high level control

Turbine high level control is taken to mean control and monitoring that the turbine can carry out to ensure the continued function of the turbine, as opposed to the regulation of power through the drivetrain during normal operation. In the case of smaller near shore turbines that are low cost and easily accessible, it is likely that the optimum solution is to have little onboard control, with all turbine decision making and monitoring being carried out onshore. This method can limit scalability for arrays and may also impact the ability for a turbine to react appropriately in certain fault conditions depending on the turbine architecture. If a turbine has full on-board control with some onboard energy storage to keep the control running, it is able to react very quickly to any issues, and also can react to any fault and continue to monitor the turbine even if connection to shore is lost. This obviously involves higher per turbine cost for the control system.

2.2 Modelling

2.2.1 System behaviour

Example model types looking at turbine behaviour include the following:

- Water-to-wire or array-level models (high level).
- Turbine load case model (e.g. DNV Tidal Bladed).
- Failure Modes and Effects Analysis.
- Detailed modelling of critical subsystems e.g. stress analysis or analysis of fast response systems.

When looking at intra-array layout and control aspects, it is not realistic to include detailed modelling in a high-level intra-array model. It is, however, very important to include the constraints from aspects of detailed modelling in the intra-array level decision-making. E.g., if the control or protection strategy relies on fast feedback and response times, then many of the possible array layouts may be found to be unworkable. Conversely, for simple systems with limited control, the extreme load events that the system must withstand may be much greater, having a large impact on infrastructure size and therefore on O&M practicalities, therefore the array architecture and fault tolerance limitations will also be very different.

2.2.2 Reliability and maintenance

When making array level decisions, it is important to have a holistic understanding of the reliability and maintenance aspects of all subsystems. Where best to locate different components may well come down to the achievable maintenance interval, reliability, or marine operations. For example, locating a lower reliability system on a substructure which otherwise requires zero maintenance has a much greater LCOE impact than locating that same system in a subsea hub which requires regular access anyway.

The above may sound obvious, however these are aspects which are easy to overlook and difficult to quantify. This is exacerbated by the lack of data or inappropriate data available for making valid reliability assessments in a tidal environment. Reliability data on components from salt-laden oil and gas or marine environments are unlikely to be valid for the relatively controlled cool and dry environment inside a tidal turbine nacelle, and the low flow, deep and sterile environments that subsea connectors are normally used in are highly unrepresentative of the energetic near-surface tidal environment. Similarly, choosing a component that according to the manual requires careful cleaning and drying before connection is unlikely to lead to high reliability if the operational constraints mean that in reality this task will likely end up being carried out on-deck surrounded by sea-spray within the timespan of a tidal slack. The use of available reliability data combined with input from experienced tidal personnel provides a very different reliability model than when relying on datasheets alone.

3 Array Design

This section first summarises some of the considerations taken account of when designing arrays, before covering design tools that can assist with array design development in section 3.2. More detail is then given in section 3.3 on the considerations for designing the intra-array electrical layout, modelling using the example of the DTOceanPlus Energy Delivery tool, and some initial results from modelling early-stage arrays in this tool. Finally, the control and operation of the array is covered in section 3.4.

3.1 Summary of array design considerations

There are many aspects that need to be considered when planning and designing an array of ocean energy devices, some of these are summarised in Table 3.1, noting this is far from exhaustive and these can often result in conflicting requirements. The IEA-OES has also published a framework for the evaluation of ocean energy technologies that covers a wide range of criteria to be considered [1].

Table 3.1. Summary of interlinking and often conflicting parameters influencing array design (non-exhaustive)

Theme	Parameters/notes/examples
High level design choices	<ul style="list-style-type: none"> Type of turbine, e.g. 2-bladed horizontal axis. Physical size of turbine and blades, rated power, cut-in/cut-out velocities... Whether on a floating platform or fixed to a structure or seabed...
Hydrodynamic energy capture	<ul style="list-style-type: none"> Energy capture is influenced significantly by the array layout and device spacing. The hydrodynamics of array interaction is a critical aspect for power generation. Site and environmental conditions, which can be very localised for tidal stream sites, varying temporally on various scales and spatially in three dimensions.
Design of other subsystems	<ul style="list-style-type: none"> Structural design of device Design of transmission/generator system(s), e.g. direct drive, gearbox, hydraulics... Type and design of moorings and/or foundations, shared or per device, how they will be installed and maintained...
Electrical	<ul style="list-style-type: none"> Topology of intra-array network and export cable to shore. Voltage levels and requirements for transformers. Balance between active and reactive power. Cable routes influenced by device positions, distance to onshore landing point, seabed type and bathymetry, current speeds, exclusion zones... Cable landing point constraints – one or multiple cables, landfall method... This also influences and is influenced by the choice of cable installation and protection methods.
Installation and O&M	<ul style="list-style-type: none"> How will the devices and cables be assembled, transported, installed, operated, inspected, maintained, and eventually decommissioned? Inspection/maintenance carried out in-situ, on a vessel, at port... Type and frequency of predictive/corrective maintenance regime used. Types of vessels available, conditions they can operate in, distance to port...
Reliability/operability	<ul style="list-style-type: none"> Both of individual components, and interactions between them, heavily influenced by design choices and installation/O&M methods. Amount of redundancy in design (trade-off against cost?). Complexity of the overall design i.e. fixed pitch vs. variable pitch design, or direct drive vs. gearbox.
Environmental/social factors	<ul style="list-style-type: none"> Many factors, both positive and negative, to consider. Very important to consider, but beyond the scope of this report.

Theme	Parameters/notes/examples
Economics and risk	<ul style="list-style-type: none"> All these factors (and more) must be considered within an economic framework, balancing costs & risks to maximise LCOE and return on investment, again complex but beyond the scope of this report.

The design of the intra-array layout and control is just one piece of a complex multi-dimensional puzzle. This results in a difficult optimisation problem, a complex multi-disciplinary challenge. A range of informed specialists, most likely a wide team with differing skillsets, are required to effectively design an ocean energy project. The often-conflicting requirements in these different areas will likely require multiple iterations to develop suitable and viable product and projects.

3.2 Example design tools for array modelling

Design tools have been developed to assist with the challenge of modelling the many aspects of array design. Some design tools focus on only certain aspects, while others such as DTOcean and DTOceanPlus try to encompass most aspects at a higher level. Within the EnFAIT project, DTOcean and DTOceanPlus are being used, both to inform the project and to further test and develop these open-source tools.

The DTOcean project¹ produced a first generation of freely available open-source design tools for wave and tidal energy arrays [2, 3]. The tools were released in January 2017. They are split into five modules or design stages: (1) Hydrodynamics, (2) Electrical sub-systems, (3) Moorings and foundations, (4) Installation, and (5) Operations and maintenance. A global decision tool containing optimisation routines, evaluated each stage of the design, and the whole design, using three thematic assessments: Economics, Reliability, and Environmental.

These tools were further developed in the DTOceanPlus project², with a second-generation of open-source tools released in August 2021. The resulting suite includes the following tools [4]:

- **Structured Innovation (SI)** for concept creation, selection, and design.
- **Stage Gate (SG)**, using metrics to measure, assess and guide technology development.
- **Deployment Design** tools, supporting optimal device and array deployment.
 - **Site Characterisation (SC)**, to characterise the site, including metocean, geotechnical, and environmental conditions.
 - **Machine Characterisation (MC)**, to characterise the prime mover.
 - **Energy Capture (EC)**, to characterise the device at an array level.
 - **Energy Transformation (ET)**, to design PTO and control solutions.
 - **Energy Delivery (ED)**, to design electrical and grid connection solutions.
 - **Station Keeping (SK)**, to design moorings and foundations solutions.
 - **Logistics and Marine Operations (LMO)**, to design logistical solutions and operations plans related to the installation, operation, maintenance, and decommissioning operations.
- **Assessment** tools, used to quantify key parameters and evaluate projects and designs.
 - **System Performance and Energy Yield (SPEY)**, to evaluate projects in terms of energy performance.
 - **System Lifetime Costs (SLC)**, to evaluate projects from the economic perspective.
 - **System Reliability, Availability, Maintainability, Survivability (RAMS)**, to evaluate the reliability aspects of a marine renewable energy project

¹ Funded through European Community's Seventh Framework Programme under grant agreement № 608597

² Funded through the European Commission's Horizon 2020 Programme under grant agreement № 785921.

- **Environmental and Social Acceptance (ESA)**, to evaluate the environmental and social impacts of a given wave and tidal energy projects.
- These are supported by Data Management tools that maintain the underlying data for ocean energy projects and allow sharing of design information.

There are many other design tools used in ocean energy, although these tend to focus on a particular phase of the design process (e.g. optimisation of device energy capture) [2]. Both freely available/open-source software and commercial tools are available, with a review conducted for the DTOceanPlus project presented in [2]. There are also a range of bespoke academic or in-house models and tools developed in a range of software environments. The DTOceanPlus review did not identify any other tools for intra-array layout and control for ocean energy, although academic algorithms and commercial tools are available for offshore wind farm cable routing, as well as for areas that are applicable across other industries such as marine operations modelling.

It should be noted that all design tools have limitations, however, and can only answer the specific questions asked within the framework and assumptions of the code. It is important to understand and be aware of these limitations when using the tools.

3.3 Example of intra-array electrical architecture modelling

This section presents examples and lessons from modelling the intra-array electrical architecture of early-stage ocean energy arrays using the DTOceanPlus Energy Delivery (ED) tool within the EnFAIT project.

As summarised in section 3.1, there are many (often conflicting) requirements to consider when designing an ocean energy array. For the initial electrical architecture design, it can usually be assumed that the array layout and device positions have been set based on maximising energy and avoiding constraints, as well as considering aspects like ease of installation and O&M. The exact locations may vary slightly during detailed design and the installation, but this will not significantly affect the electrical cabling.

The types of electrical architecture to consider will depend on the key parameters including the size of each individual turbine, the number of devices in the array, and the distance for the export cable to the onshore landing point, substation, or grid connection point.

For small arrays close to shore, it may be convenient to install individual export cables to shore for each turbine. This is the case for both of the tidal arrays currently operating: the Nova array in the Bluemull Sound, Shetland, and MeyGen Phase 1A in the Pentland Firth between the Scottish mainland and Stroma. Each comprises four turbines with individual cables to shore. Alternatively, the devices could be connected to each other in a radial or daisy-chain configuration, as was proposed by MCT for their 8MW four device Kyle Rhea project [5], although this did not progress beyond the planning stage.

For larger arrays, some form of offshore aggregation will likely be used. This could be a subsea hub, connecting multiple turbines to a single export cable, all operating at the same voltage. This is planned for the next phases of both the Nova and MeyGen arrays [6]. For large arrays, or where the cable lengths are significant, an offshore substation may be required to increase the voltage between the intra-array cables and the export cable(s) and thus reduce losses to an acceptable level.

The sizing of electrical cables is a balance between cost and electrical losses. Larger conductor cross-sections and higher voltages both reduce losses, but they are more expensive to procure and install. As losses are proportional to cable length, this also has a significant impact, so the aim is to minimise cable

length while meeting other requirements. The design of the array therefore needs to balance the voltage levels used for the different stages of the transmission to shore, i.e. device, intra-array cables, export cable(s), and offshore substation(s) as appropriate.

The routing of intra-array cables and export cables to shore needs to take account of the seabed bathymetry and geological conditions. The cable installation, and possible protection, methods will depend on the seabed conditions. Some methods may also have maximum slope limitations to be considered. For tidal stream projects, the maximum current velocities experienced close to the seabed may also have a bearing on the design choices for cable routes. At a higher level, there may be specific exclusion zones within the project lease boundary that must be avoided, be this for environmental designations or other sea users.

3.3.1 Using the DTOceanPlus Energy Delivery tool to design the electrical layout

As described in DTOceanPlus documentation [4], the Energy Delivery (ED) tool designs the electrical network to transmit power from devices to shore, including the:

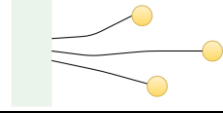
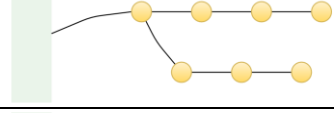

- Array network – cables between Ocean Energy Convertors (OEC)
- Collection point (CP), which can be a substation with voltage transformation or a passive hub.
- Transmission cable to the Onshore Landing Point (OLP)

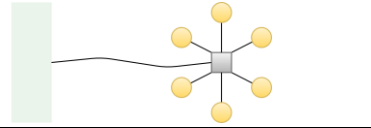
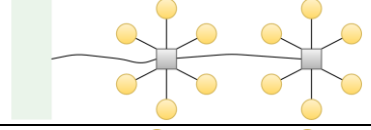
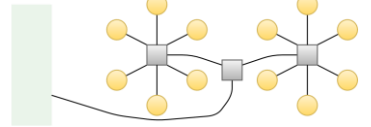
The design is based on user choices, design parameters from other tools, and a catalogue of typical electrical components.

Six different network topologies are considered within ED, shown in Table 3.2 and can be summarised as follows. Direct connections to shore for each device. Radial arrays with or without an offshore CP, where devices are connected in series. Star arrays, with each device connected to a CP, which can have one or more clusters that may optionally be connected via another (transmission) CP. Radial strings may be more efficient in terms on minimising cable length, whereas star arrays can make it easier to remove individual devices for maintenance without impacting any devices connected in series. Other network topologies are possible, including loops and branching trees, but these have not yet been implemented in DTOceanPlus Energy Delivery.

For CPs where voltage transformation is required, the tool designs a surface-piercing substation on a monopile foundation. Where no voltage transformation is needed, a bed-mounted sub-sea hub is assumed. Future refinements to the tool may consider other options.

Table 3.2. Details of electrical network topologies in Energy Delivery [4].

Network topology (short name)	Array CP	Transmission CP	Simplified diagram
Direct to shore (Direct)	No	No	
Radial	No	No	
Radial with transmission collection point (Radial + CP)	No	Yes	

Network topology (short name)	Array CP	Transmission CP	Simplified diagram
Single cluster star (Single star)	No	Yes	
Multi-cluster star (Multi-star)	Yes	Yes	
Multi-cluster star with transmission CP (Multi-star + CP)	Yes	Yes	

The Energy Delivery tool uses a lookup table to determine potentially suitable export voltages, which are a function of array rated power and distance to shore. Future improvements to the ED tool may refine this voltage selection. For network configurations without a collection point (i.e. direct connection and radial without CP), the user needs to select a device voltage that meets these limits. This may require a transformer on the device.

The tool selects suitable components from a reference catalogue. It calculates electrical losses using the PyPower power flow solver for a range of design permutations. It then returns the top result in terms of cost-of-energy of the electrical subsystem, i.e. the total cost of the electrical components divided by the annual energy delivered to shore. Cost proxies are used for the cable and collection point installation, to assess the relative merit of the different design permutations. These are not included in the overall cost-of-energy as more accurate values can be calculated afterwards using the LMO tool, however the installation costs still need to be considered when comparing different networks.

3.3.2 Initial results from modelling early-stage ocean energy arrays with Energy Delivery tool

To explore the relative importance of different parameters on the design of the electrical cabling for early-stage ocean energy arrays, a systematic study was performed using the DTOceanPlus Energy Delivery tool [7]. This explores the impact of varying several key parameters:

- Array distance to shore and export voltage,
- Array layout and device spacing,
- Array topology/type,
- Device power and voltage.

It is important to stress that the specific results presented here are heavily dependent on the assumptions made, limitations in the scope of each scenario, and the fact that only the array electrical infrastructure is being considered. However, they are illustrative of some of the sensitivities that can be explored with an array modelling tool such as DTOceanPlus. For this reason, full details of each scenario modelled are not given here. It is also noted that the results presented here are not linked to the EnFAIT array or the Nova turbines.

Further testing using the DTOceanPlus tools is ongoing within the EnFAIT project, which will hopefully address some of these limitations. This will be reported in deliverables D10.5 DTOcean: Comparative with initial predictions, and D10.6 DTOcean: Conclusions, expected to be published in summer 2022 and early 2023 respectively.

As the distance between the array and onshore landing point (OLP) increases, the length of cable will also rise proportionally. This will increase both capital and installation costs, plus the losses within the cable (assuming other parameters remain the same). At some distances, the losses will become so large that a higher transmission voltage will be required.

Device spacing and physical arrangement

There is not yet consensus on optimal array layout and device spacing. Various grids, rows, staggered rows, etc. are often suggested, the parameters of which will be dependent on the shape and type of device. Individual devices may also be subject to micro-siting, to suite the detailed local conditions. This is being explored within the EnFAIT project, with the plan to reconfigure the array layout.

The intra-array electrical network is not the primary driver for the array layout, it will usually largely be determined to optimise the hydrodynamic energy capture of the array of devices. Access requirements for installation and O&M may also dictate minimum device spacing or affect layout pattern preferences, e.g. provision for mooring lines or cable-laying bend radii.

The total length of intra-array cable will increase proportionally with device spacing, for all networks with some form of offshore collection. The total cable length required for direct connections will also increase with device spacing but may not be as noticeable. Arrays with devices in non-uniform grids or arranged in rows may have preferential routes for connecting devices to minimise cable length, e.g. connecting devices along rows. Tidal current velocity and direction may also influence the cable route chosen.

Array topology and device/transmission voltage example

To investigate the various network topologies considered in the Energy Delivery tool, arrays of between 4 and 64 devices were modelled for devices of increasing power and voltage. Note that smaller cables may be cheaper to install, but this is not considered in this analysis. More detailed analysis, including this type of sensitivity, will be provided in D10.6.

Figure 3-1 shows example results, split by network type, for arrays of 500kW devices. These results can also be visualised by comparing the network types for each device voltage, as shown in Figure 3-2.

The maximum distance considered suitable at 690V is 1.3km, therefore this voltage is not considered for the direct or radial (without CP) network topologies. No technically feasible solutions were found for radial networks at 3.3kV with 32 or more devices. Direct connections have an increased cost of energy with more devices, as each additional device requires an individual cable, and these get longer as the array becomes bigger.

The increased cost for the 64-device radial array appears to be a result of the significant increase in size of the array and increase losses due to the larger total power. To better assess the suitability of network options would require comparison of a wider range of parameters, such as total cable length, array and export voltages, losses, installation costs, etc.

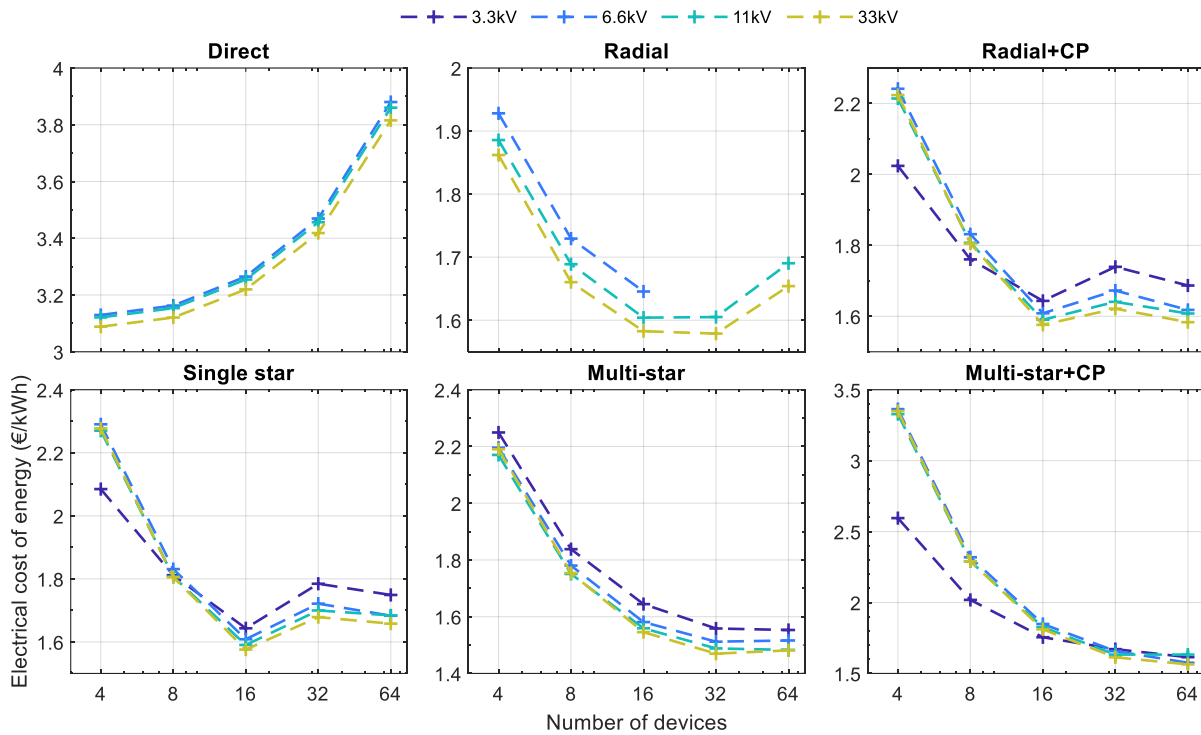


Figure 3-1. Example relationships of electrical cost-of-energy as a function of number of devices in the array and device voltage, for six network topologies. Note that the y-axis scale is different between subplots and the costs are illustrative – depending on many other parameters not fully explored here. See Table 3.2 for details of network types.

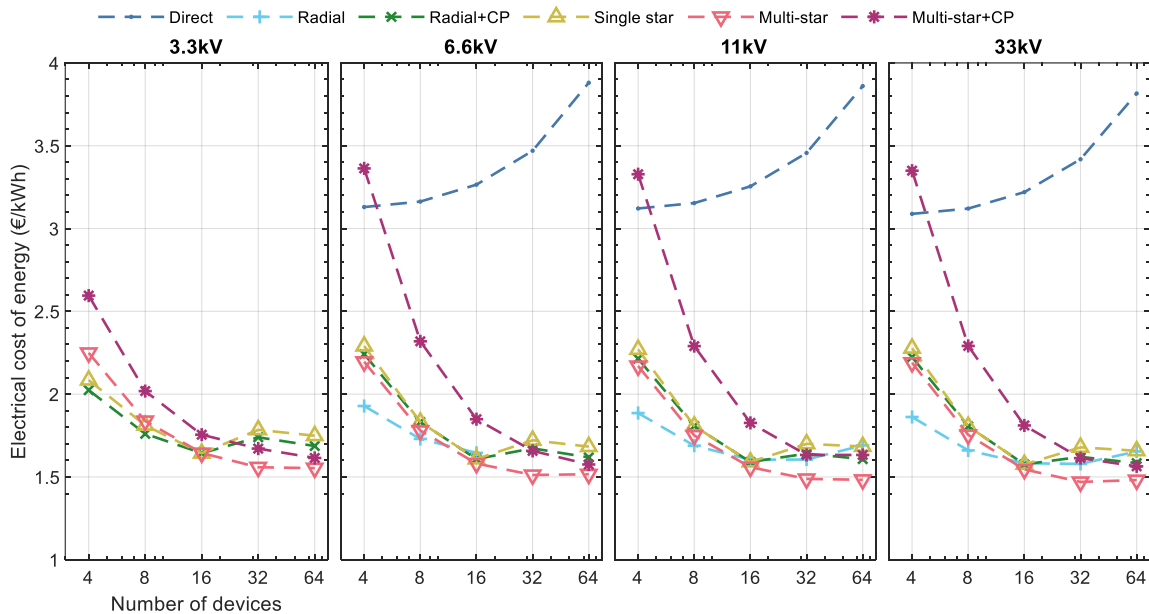


Figure 3-2. Example relationships of electrical cost-of-energy as a function of number of devices in the array and network topologies, for four device voltages. Note that the costs are illustrative – depending on many other parameters not fully explored here. See Table 3.2 for details of network types.

Cable power and voltage optimisation example

To investigate the optimal transmission voltage for direct-to-shore networks, the electrical cost of energy (excluding installation) and the electrical losses are plotted in Figure 3-3 for four different powers.

Particularly for 1MW and 3MW, there is a relatively clear trend in the electrical cost of energy, reaching a minimum at 11kV in both cases, although only slightly cheaper than 6.6kV or 33kV. For the 100kW cable, there is little difference in cost between the lowest three voltages. In all cases at 100kW the electrical losses are very low, suggesting the selected cable is perhaps over-rated, hence the much higher cost of energy than the other power ratings.

It should be noted that many other turbine and array components such as connectors will increase in cost with voltage, however this is not considered in this analysis. Additionally, many components may not be commercially available for the highest voltages, or only available with high power ratings and associated cost. Addressing these limitations will change the shape of these curves and affect the optimum voltage of the system as a whole as opposed to focussing on the cable. This is a good example of where high level models have the potential to provide useful guidance, however use of the outputs without an understanding of the model inputs and limitations would not result in the optimum design decisions.

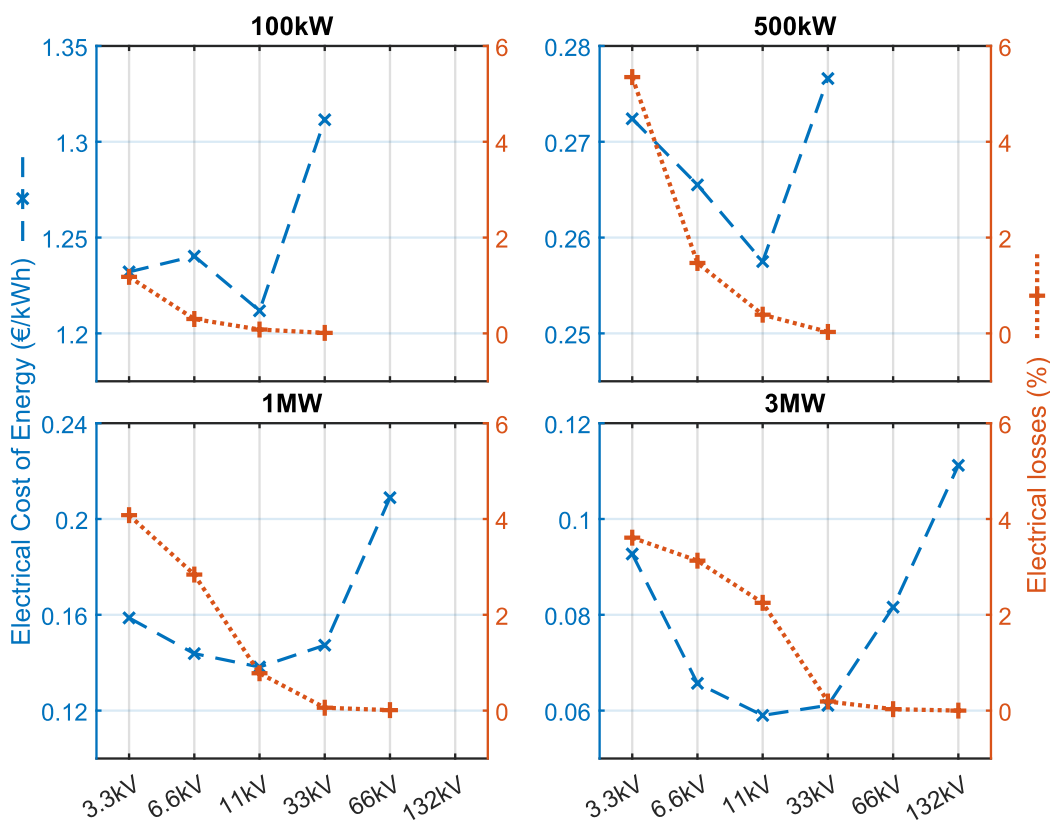


Figure 3-3. Example relationships of electrical cost-of-energy (left axes) and electrical losses (right axes) as a function of transmission voltage at four different power ratings. Note that the left y-axis scale is different between subplots and the costs are illustrative – depending on many other parameters not fully explored here.

3.4 Intra-array control and operation

The choices made above will change what array level control is required, and what fault tolerance the array level control can provide. However regardless of what options are chosen, decision-making and control at intra-array level is mostly about ensuring that turbines are operated at the optimum times, and that the optimum amount of energy is released to the grid.

3.4.1 Receiving status and health data from the turbines and associated systems

Decision making relies on receiving information from the turbines, and directly or indirectly from the environment:

- Tide flow speed (and direction) – this may be real or modelled data.
- Other environmental conditions e.g. wind speed, wave conditions – particularly for surface or near-surface technologies.
- Status of each turbine (and any intermediate infrastructure e.g. hubs), including any permanent or temporary limits on their operation. Depending on the level of on-turbine control, this may be a simple output of status codes, or less processed data that must be managed and assessed at array level.

For any warnings or faults not automatically managed at turbine level, these can then be assessed at array level, whether automatically or by an operator.

3.4.2 Receiving demand from the grid and other parties

At present, grid connected arrays can run with relatively simple decision-making. Typically, it makes most commercial sense to put to the grid as much energy as the grid operator allows. However, with micro-grid or smart-grid systems, the ability to react to upcoming demand and to manage stored energy at a smaller and more immediate scale is likely to become more and more important and commercially beneficial to provide a stable enough grid without reliance on fossil fuels. This is particularly relevant to many tidal areas which are often near the edge of the grid, where improved resilience would be highly beneficial.

In some cases, there may be other sources of information from outside the array that must be considered e.g. any operational limitations that are a condition of the array's operating licence, and thus may dictate operational constraints beyond the state of the tide, grid, or array.

3.4.3 Sending operational demand to the turbines and any energy storage systems

With the inputs above, the array level controller will then set target powers for all devices. Particularly where grid constraints limit the allowable generation, array level control can then be used to determine the optimum generation strategy, e.g. whether to have more turbines operating at lower powers or fewer at higher powers, and also whether there is a priority order. These decisions will be based on factors such as relative wear/aging at different powers, operational running time of each turbine, and geographical differences, e.g. the turbine at the 'sweet spot' of the tidal stream being switched on first as the tidal-slack finishes. At the current maturity and scale of tidal arrays, these decisions are relatively unimportant and, in some cases, may be determined by an operator, however as array sizes grow automated decision-making at this level will become much more important for optimising array LCOE.

4 Array reliability and availability

The reliability and availability of the array depends both on that of the individual turbines, but also the electrical cables delivering power to shore and providing control signals to the turbines. A fault in the export cable could impact the whole array. This impacts energy production and therefore directly on revenue generated and overall profitability. Therefore, reliability and availability are always important.

As discussed above, there are different scopes for modelling, either focusing in more detail at the component/subsystem level, or at a higher system-level across the whole array. For component/subsystem level analysis, there are existing failure modes and effects analysis (FMEA/FMECA/RAMS) methods available which can easily be applied to tidal turbines as well. However, understanding the intra-array level of reliability and availability is still a novel subject.

4.1 Component level assessment

Actively maintaining a high level of technical reliability and operational availability of an array requires an assessment of potential failures that might occur during operation at a component level. Understanding the environment and the operational context in which the turbines will operate allows us to gain an understanding of possible failure causes which might occur during the lifespan of the turbine and each component. Potential failures during operation pose a risk and therefore require a form of mitigation, either in the design phase in which choices are made with regards to what kind of components to use in the turbines, or in the operational phase through performing preventive maintenance in order to maintain the inherent reliability of each component and the turbine as a whole.

The analysis done at the component level consists of an FMEA/FMECA analysis. The FMEA/FMECA methodically assess each component; how the component can fail, the expected component life (mean time between failure), the effect of failure on the turbine and electricity generation and how the failure can be prevented or mitigated. The end results can either be a design improvement, for example choosing more rigid components or to change from gearbox driven generator to a direct drive generator to remove complexity of components and with that the risk of mechanical failures. But the result is also the creation of preventive or predictive maintenance tasks, which need to be performed at calculated intervals in order to keep the condition of components at the highest level of reliability.

FMEA/FMECA analysis only investigates individual components, or no higher than system level. If and how the failure of an individual turbine affects the array as a whole is beyond the possibilities of an FMEA/FMECA analysis. To understand how the reliability and availability impacts on the array level performance a different, more holistic approach than FMEA/FMECA is required. With the use of tools like DTOcean and DTOceanPlus, a step is made to allow the assessment of the reliability and availability on an array level.

4.2 Tools for modelling reliability and availability at array level

Design tools such as DTOcean and DTOceanPlus are being developed to model the reliability and availability of a whole array at a system level. The DTOceanPlus RAMS module is used to collate design information from the design modules, and then assess the reliability, availability, maintainability, and survivability of the devices and array. The design of the ocean energy array is represented by a structured hierarchy considering both the physical and electrical connections between components. This includes the fault-tree logic of interdependence between subsystems. From the component level failure rates, and

how these components are interlinked, it is possible to estimate the overall array reliability and availability.

The DTOceanPlus project also developed a structured digital representation for ocean energy projects [8], a step towards having a “digital twin” of the array. To fully capture the main aspects of an ocean energy system, the digital representation framework accounts for:

- Elements of the technology design (physical domain), phases of the technology lifecycle (process domain), and constraints from the context (external environment).
- A dimension that describes hierarchical connections among subsystems and components.
- A dimension accounting for the individual and specific components of the system.

Accurately representing the interlinkage between components is important for any system-level tool.

4.3 Operation and maintenance in a marine energy environment

Operating in a marine energy environment brings both benefits and challenges for reliability and availability. Some of the key considerations are as follows:

4.3.1 Design for inspection and maintenance

For most varieties of tidal technology, in-situ physical access to the device is limited to diver or ROV intervention during slack-tide, and therefore bringing the turbine to shore is the normal maintenance method. This affects the cost versus reliability (or maintenance interval) balance, in particular for lower cost components. This is similar to the trend in offshore wind, where tasks which are carried out manually in many industries (e.g. regreasing) are automated, or a higher specification part is selected as it has a lower through-life cost once the cost of O&M is included. This includes the addition of sensors and their associated communication systems, which are used instead of a physical inspection.

These considerations may also affect the system architecture design, as choice of array layout must take into account the accessibility of inherently short-lifetime or low-reliability components. For example, if not practical to design them out, it would be preferable to place shorter-lifetime components onshore rather than in a subsea hub even if that resulted in a slight cost increase elsewhere.

Lastly, this makes quality control and pre-deployment commissioning checks vital as post-deployment intervention is limited.

4.3.2 Relative cost and availability impact of operations

OPEX represents a large proportion of the overall cost of marine and offshore energy. As such it is essential that this is considered in depth when selecting both device and array design.

It is likely the cost, vessel requirements and operational weather windows will be different for maintenance, deployment or recovery of different parts of array infrastructure. Understanding this impact using real-world experience and offshore operation modelling tools is important and can have substantial impact on design choices in order to optimise array cost e.g. as a simple example, an intervention requiring retrieval of the substructure of a seabed mounted turbine would be very costly as they are large and heavy, and therefore designing substructures to be maintenance free and moving any complexity elsewhere is likely to be a more cost-effective decision overall.

4.3.3 Effect of the environment on reliability

The tidal environment should be considered when assessing the reliability of components or systems, and in particular when looking at manufacturer's or data-book reliability data.

- External components are subject to energetic water flow, biofouling and corrosion. This is often very different to other marine environments e.g.
 - The sector has seen reliability issues with connectors which were originally designed for the deep, dark and still water found in offshore subsea environments.
 - Submersed turbines are not in challenging corrosion conditions such as the near-surface or splash zone, and therefore corrosion is far less challenging than for many marine and O&G applications.
- Internal components are protected in a well-sealed and cooled atmosphere, often leading to very benign conditions, and therefore longer life than experienced by most other marine or offshore industries.

The considerations above have many implications for the array design in section 3.3, and also in the accuracy of system reliability modelling discussed above. These questions cannot be solved by computer models alone, at least until more tidal-specific reliability data is available, and highlight the need for input from experienced engineers.

5 Conclusion and Recommendations

In this report we have discussed the key considerations for optimising the design and operation of intra-array layout and control. We have also presented examples of areas where modelling tools could be used to inform this optimisation. Due to the relatively early stage of tidal array development, and the site and device specific nature of much of the optimisation, this report does not try to present an optimised design, but rather presents key aspects that we believe should inform array design.

Intra-array layout design is a highly device and site-specific subject. Optimising the electrical system layout must be done in conjunction with the turbine and array control system level design, as well as the site electrical constraints. Combining this with operation and maintenance considerations results in a complex optimisation problem that cannot easily be solved by computer models alone.

In summary, this report presents the following recommendations:

- Holistic design is vital, including consideration of operation and maintenance aspects as well as site-specific aspects. As per-site design is rarely cost-effective, as has occurred in similar industries it is likely a suite of design layout options for different grid requirements, types of site and sizes of array will be developed by turbine developers as the industry matures.
- Modelling tools can be extremely valuable for array design, but also have the potential to be very misleading. They require a user who understands the inputs and validity limitations of those tools, and their interaction with the broader design. As such, tool developers should ensure that the assumptions and input data used are easily understood and customisable, as the performance, costs and availability of different subsystems and operations will change rapidly as the technology matures. For higher-level modelling, it is likely that in-house or tailored modelling tools will continue to be important, as they allow in-house or device specific knowledge to be included within the model.
- Accurate reliability and availability optimisation is only achievable with good inputs, and non-tidal-specific data is often not representative. As such, involvement of experienced engineers and maximising total running-hours of a design are key to accelerating the maturity of tidal technology.

The EnFAIT project continues to provide a fantastic opportunity to utilise and progress the recommendations above, paving the way for the first commercial arrays and the next generation of tidal technology.

6 Further Work

The concluding findings of WP9 (Optimise array reliability, maintainability & availability) will be reported under D9.8 WP9 report: conclusions and future recommendations.

More outputs from the assessment of the DTOcean and DTOceanPlus tools to model the EnFAIT array will be published in D10.5 DTOcean: Comparative with initial predictions, and any further lessons that can be learnt for the sector in D10.6 DTOcean: Conclusions. Development of detailed models looking at array interaction and wake effects have also been developed as part of the EnFAIT project, and the remaining work will be reported under D10.9 AIM: full array operational report and D10.10 AIM final report.

Real-world knowledge is continuously being developed as the EnFAIT array is operated and extended, with much of the focus of the latter parts of the project being on array optimisation. In addition the continued operation of multiple turbines is an invaluable source of real-world knowledge, with the EnFAIT project providing increased inspection and learning opportunities compared to that available in a purely commercial array. Findings from the final operation and decommissioning stages of the extended array will be available in the final reports D6.8 and D7.4.

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