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ENFAIT ENABLING FUTURE ARRAYS IN TIDAL

DTOcean: Conclusions



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Abbreviations and Definitions

| | |
|----------|---|
| AEP | Annual Energy Production |
| API | Application Programming Interface |
| CAPEX | Capital Expenditure |
| CP | Collection Point |
| DTOcean | Design Tools for Ocean Energy Arrays |
| EC | Energy Capture (DTOceanPlus module) |
| ED | Energy Delivery (DTOceanPlus module) |
| ESA | Environmental and Social Acceptance (DTOceanPlus module) |
| ET | Energy Transformation (DTOceanPlus module) |
| GUI | Graphical User Interface |
| LCOE | Levelized Cost of Energy |
| LMO | Logistics and Marine Operations (DTOceanPlus module) |
| MC | Machine Characterisation (DTOceanPlus module) |
| MM | Main Module (DTOceanPlus module) |
| O&M | Operation and Maintenance |
| OPEX | Operational Expenditure |
| PMSG | Permanent Magnet Synchronous Generator |
| PTO | Power Take-Off |
| q-factor | Array Interaction Factor (calculated as the AEP of the array divided by the AEP of the same array without considering the interaction). |
| RAMS | System Reliability, Availability, Maintainability, Survivability (DTOceanPlus module) |
| SC | Site Characterisation (DTOceanPlus module) |
| SG | Stage Gate (DTOceanPlus module) |
| SI | Structured Innovation (DTOceanPlus module) |
| SK | Station Keeping (DTOceanPlus module) |
| SLC | System Lifetime Costs (DTOceanPlus module) |
| SPEY | System Performance and Energy Yield (DTOceanPlus module) |
| TEC | Tidal Energy Converter |
| UTM | Universal Transverse Mercator (coordinate system) |
| WEC | Wave Energy Converter |
| WGS84 | World Geodetic System 1984 (coordinate system) |
| WP | Work Package |

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.

One of the purposes of Work Package (WP) 10 of the EnFAIT project is to validate and refine the DTOcean, and subsequently the DTOceanPlus, open-source design tools for ocean energy arrays. This document summarises the testing and application of both the DTOcean and DTOceanPlus tools to model the real-world Nova tidal turbine array. It sets out the lessons learned from this work, as well as providing guidance for using and refining the DTOceanPlus tools. It aims to be useful for both Nova and the wider ocean energy sector. It is to be submitted to satisfy deliverable D10.6 of the EnFAIT project and to be made available for public dissemination.

1.2 Scope and aims

As noted above, one of the main objectives of WP10 is to validate and refine the DTOcean design tools based on experience during the EnFAIT project design, development, and operation. This has been expanded to include the DTOceanPlus tools which were developed and released within the timescale of the EnFAIT project. This work has been undertaken in multiple stages using the latest versions of the tools as these have developed in parallel with the EnFAIT project (more detail is given in section 3.1 after the description of the tools).

Within tasks 10.3–10.6 of the EnFAIT project, the use of the DTOcean and DTOceanPlus tools had three broad objectives:

1. Understand how well the tools work, especially when modelling a small tidal array such as the Nova Shetland Tidal array in EnFAIT.
2. Identify limitations and potential areas for improvement, and then give feedback to improve the DTOceanPlus tools that were being developed concurrently with the EnFAIT project.
3. Give any feedback to assist with the planning of future arrays of turbines

This deliverable (D10.6) concludes the assessment of the DTOcean and DTOceanPlus tools. It presents lessons learnt from using these tools, as guidance for their future use and development. The assessment of the DTOcean and DTOceanPlus tools was initially reported in D10.1, D10.3, D10.4, and D10.5, which are summarised in section 3 for completeness.

Feedback from using the DTOcean and DTOceanPlus tools in the EnFAIT project has already informed the design of DTOceanPlus; it has also helped to identify and guide future improvements to the DTOceanPlus tools and documentation. The DTOceanPlus documentation has been developed and updated with lessons learnt from the use of DTOcean and DTOceanPlus within the EnFAIT project. It will be further refined following the submission of this deliverable within the remainder of the project.

Please note that this document presents the outputs from the DTOcean and DTOceanPlus suite of tools. It does not fully represent the design of the actual deployed array, nor is it proposed to change the existing array design based on these outputs. A comparison of the tool outputs with the actual array design choices

made by Nova Innovation is provided in this document to help assess the effectiveness of these design tools in modelling this type of project.

As highlighted in EnFAIT D9.7 Best Practice Report on Intra-array Layout and Control [1], the design of an array is a complex and multi-faceted problem, with many often-conflicting requirements. 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, such as hydrodynamics, structural loading, or mooring forces, 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 this and future projects and to further test and develop these open-source tools.

1.3 Outline

The document is structured as follows:

- Section 1 describes the EnFAIT project's motivation and the objective of the present work.
- Section 2 introduces and summarises the capabilities of DTOcean and DTOceanPlus, open-source design tools used for the optimisation of array design.
- Section 3 summarises how these tools are used in WP10 of the EnFAIT project, including a recap of the previous deliverables this was reported in.
- Section 4 presents lessons learnt and guidance for: the development and optimisation of future arrays; use of the DTOceanPlus design tools; and future development of the tools.
- Section 5 offers conclusions from the testing of DTOcean and DTOceanPlus tools compared to the design of a real-world array, plus summarises next steps and future work.

2 DTOcean and DTOceanPlus design tools

The DTOcean project¹ produced a first-generation of freely available open-source design tools for wave and tidal energy arrays [2]. DTOcean stands for Optimal Design Tools for Ocean Energy Arrays. The first version of the DTOcean tools were released in January 2017 and are described in section 2.1. DTOcean version 2.0 was released in July 2019 and builds on the same codebase. This release fixed several problems identified with the original version and implemented a full Levelized Cost of Energy (LCOE) calculation [3].

Within the timeframe of the EnFAIT project, the DTOceanPlus project² further developed the tools into a second-generation of open-source design tools for ocean energy [4]. These were then demonstrated with real-world cases from several technology developers, including Nova Innovation. The DTOceanPlus tools were released in August 2021 and are described further in section 2.2.

Note that for both DTOcean and DTOceanPlus, the terms ‘tool’ and ‘module’ are used relatively interchangeably to refer to the main software components within each overall suite of tools.

2.1 Summary of the DTOcean Tools and functionalities

DTOcean was a collaborative European project (Oct. 2013–Oct. 2016), which produced an open-source set of numerical tools for the optimisation of wave and tidal energy converter arrays. The DTOcean tools are modularised into five design stages which can be analysed from three thematic assessments [5]. These are shown graphically in Figure 2.1 with further details in Table 2.1. DTOcean has an internal library, consisting of a set of data that can be augmented by the user. The tool uses these to feed into the array optimisation calculations. The main library items are vessels, equipment, ports, and failure rates.

DTOcean includes a graphical application and is supported by a persistent PostgreSQL database [6]. It is only possible to run this on the Microsoft Windows platform. It should be noted, however, that the DTOcean tools are coded in Python 2, which is no longer supported.³ [7].

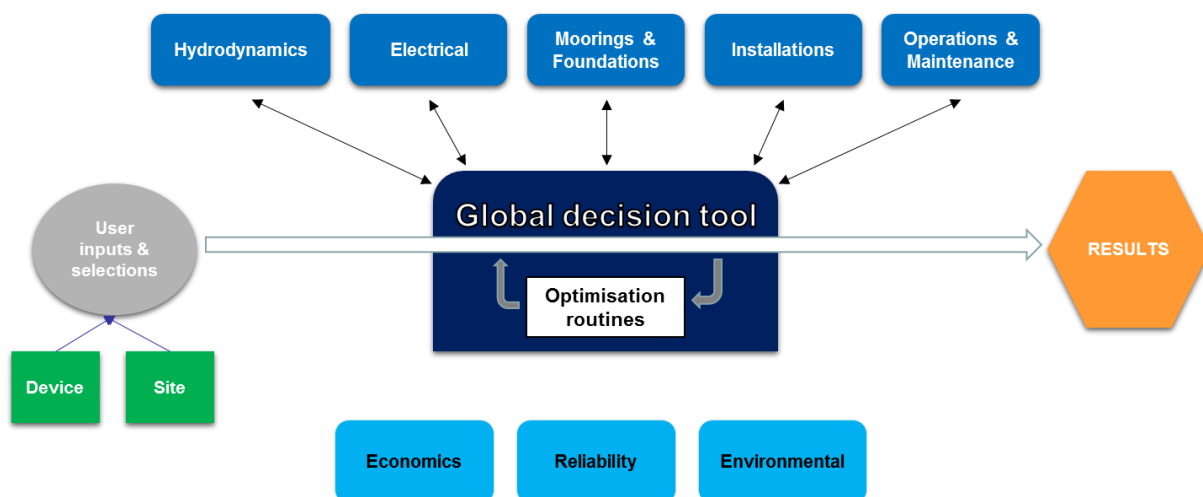


Figure 2.1. Schematic structure of DTOcean tools [8]. Applies to both v1.0 & v2.0.

¹ Funded through the European Community’s Seventh Framework Programme under grant agreement № 608597 [2].

² Funded through the European Commission’s Horizon 2020 Programme under grant agreement № 785921 [4].

³ Support for Python 2 officially ended on 1 January 2020. No new improvements or bugfixes will be released, even for critical security issues [7]. This does not prevent Python 2 code from being run, but it could present a security risk .

Table 2.1. DTOcean modules grouped into 5 design stages and 3 thematic assessments. Adapted from [6].

| | Module | Details |
|-----------------------------|------------------------------------|--|
| Design stages | 1. Hydrodynamics | Designs the layout of marine energy converters in a chosen region and calculates their power output. |
| | 2. Electrical | Designs an electrical layout for the given converter locations and calculates the electrical energy exported to shore. |
| | 3. Moorings and foundations | Designs the foundations and moorings required to secure the converters at their given locations. |
| | 4. Installation | Designs the installation plan for the energy converters and the array components. |
| | 5. Operations & maintenance | Calculates the required maintenance actions and energy losses resulting from the operation of the converters over the lifetime of the array. |
| Thematic assessments | 1. Economic assessment | Produces economic indicators for the design, in particular the LCOE. |
| | 2. Reliability assessment | Evaluates the reliability of the foundation and electrical components during the array lifetime. |
| | 3. Environmental impact assessment | Identifies the most sensitive receptors/stressors, which are combined into different environmental functions. |

2.2 Summary of the DTOceanPlus Tools and functionalities

A suite of second-generation design-tools for the selection, development, and deployment of ocean energy systems was developed and demonstrated through the DTOceanPlus project (May 2018–Aug. 2022) [9]. This built on the strong foundation of the original DTOcean tools. Five brand-new tools were added, and the functionality of those based on the DTOcean tools was greatly expanded. The complete suite of DTOceanPlus tools is shown schematically in Figure 2.2 with details of each module in Table 2.2.

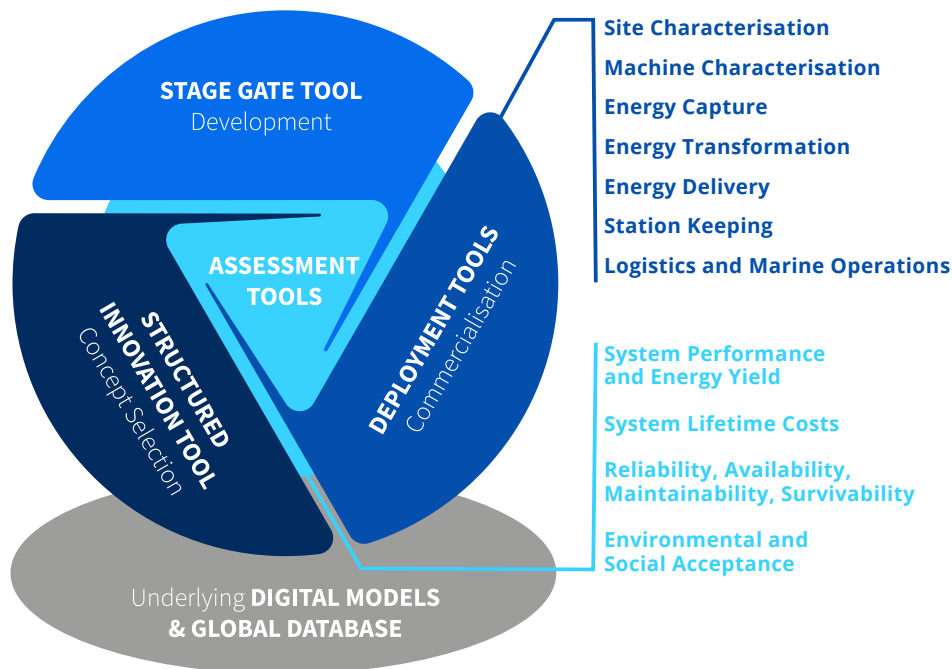


Figure 2.2. Schematic showing main DTOceanPlus tools [10].

Table 2.2. Summary of DTOceanPlus modules. Adapted from [10].

| | Module | Details |
|--|--|---|
| Deployment Design tools, supporting optimal device and array deployment. | <i>Site Characterisation</i> [†] (SC) | Characterise the site, including metocean, geotechnical, and environmental conditions. |
| | <i>Machine Characterisation</i> [†] (MC) | Characterise the prime mover, either Wave or Tidal Energy Converter (WEC or TEC). |
| | <i>Energy Capture</i> (EC) | Consider the hydrodynamic performance of devices and array interaction. |
| | <i>Energy Transformation</i> [†] (ET) | Design power take-off (PTO) and control solutions. |
| | <i>Energy Delivery</i> (ED) | Design electrical and grid connection solutions. |
| | <i>Station Keeping</i> (SK) | Design moorings and foundations solutions. |
| Assessment tools, used to quantify key parameters and evaluate projects and designs. | <i>Logistics and Marine Operations</i> (LMO) | Design logistical solutions and operations plans related to the installation, operation, maintenance, and decommissioning operations. |
| | <i>System Performance and Energy Yield</i> (SPEY) | Evaluate projects in terms of energy performance. |
| | <i>System Lifetime Costs</i> (SLC) | Evaluate projects from the economic perspective. |
| | <i>System Reliability, Availability, Maintainability, Survivability</i> (RAMS) | Evaluate the reliability aspects of a marine renewable energy project |
| Technology innovation & development tools | <i>Environmental and Social Acceptance</i> (ESA) | Evaluate the environmental and social impacts of a given wave and tidal energy projects. |
| | <i>Structured Innovation</i> [†] (SI) | For concept creation, selection, and design. |
| | <i>Stage Gate</i> [†] (SG) | Using metrics to measure, assess and guide technology development. |
| [†] New tools in DTOceanPlus. The suite of tools is supported by Data Management tools that maintain the underlying data for ocean energy projects and allow sharing of design information. | | |

DTOceanPlus is also a modular suite of tools. These can either be run together in ‘integrated’ mode, or each tool independently in ‘standalone’ mode. In the integrated mode, the tools are run sequentially, building up the design of the ocean energy project. It is noted that all previous tools in the chain need to be used in integrated mode, it is not currently possible to skip any of the design tools. In the standalone mode, the user needs to provide all input data that would normally come from other modules in the suite, in the format of the previous modules’ output. The tools can all be run in standalone mode from the main module interface, it is also possible to just install some of the modules completely independently and access them directly.

The DTOceanPlus tools are designed to work at three levels of complexity, as shown in Figure 2.3. They have fewer inputs and simpler data at low complexity, allowing a quicker analysis that can be used at early stage. At high complexity there are more complex data requirements and longer computational time, to provide more accurate results. Varying levels of complexity can be used between the different modules, however using a low complexity for one module may reduce confidence in the results of a later module.

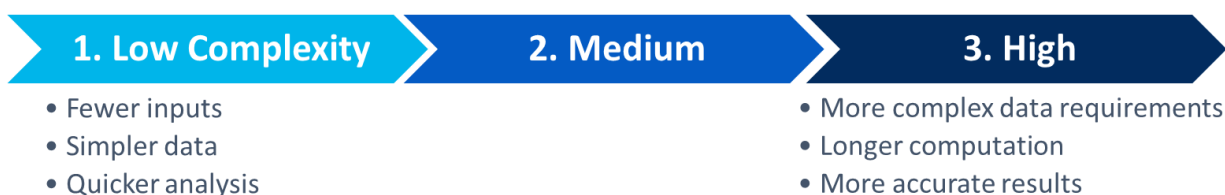


Figure 2.3. Levels of complexity within DTOceanPlus, adapted from [10].

The DTOceanPlus tools are coded in Python 3, run in Docker containers⁴, and are accessed via a web browser interface or an Application Programming Interface (API). This currently allows them to be run on Microsoft Windows, Apple macOS, and Linux computers, and would allow them to be developed as a ‘cloud-based’ web service in future. Each of the modules use the API to communicate between the “frontend” Graphical User Interface (GUI) and the “backend” or business logic that performs the calculations. The API is also used to pass data between modules, including the catalogues.

The DTOceanPlus tools have extensive online documentation⁵ that was developed in parallel with the tools. This covers both the overall suite of tools and each of the individual modules. Each section of the documentation includes an overview of functionalities and workflow, and follows an established system⁶ split into four main areas:

- **Tutorials** to give step-by-step instructions on using the tool for new Users.
- **How-to guides** that show how to achieve specific outcomes using the tool.
- An **explanation of features and calculation methods** that provides technical background on how the tool works, to give confidence in the tools and processes.
- An **API reference section** which documents the code of modules, classes, API, and GUI.

This is supplemented by the DTOceanPlus project deliverables documenting the tools’ development, testing, and demonstration. These are available through the project website⁷ and CORDIS⁸.

At the end of the DTOceanPlus project, the tools released could be considered to have a technology readiness level of TRL6, i.e. technology demonstrated in relevant environment. Within the project, the beta version of each tool was verified in standalone mode [11], [12]. The post-beta versions of the tools were then validated against the real-world projects and technologies of the industrial partners within the project: CorPower Ocean, Enel Green Power, Wave Energy Scotland, and IDOM for the five wave energy validation scenarios [13], plus Orbital Marine Power, Sabella, and Nova Innovation for the five tidal energy validation scenarios [14].

The tools were still considered development software at this initial release, with release on a public repository under an open-source licence permitting their future testing and development. As noted in the final DTOceanPlus software deliverable [15], the plan was for continued use and development of the tools beyond the end of the DTOceanPlus project, both as part of ongoing work by consortium partners, and within the framework of other projects, EnFAIT being one example.

⁴ A means of packaging software and dependencies, see section 4.3.1 and <https://www.docker.com/>.

⁵ DTOceanPlus documentation, <https://dtoceanplus.gitlab.io/documentation/>

⁶ The Documentation System, <https://documentation.divio.com/>

⁷ DTOceanPlus – Deliverables, <https://www.dtoceanplus.eu/Publications/Deliverables>

⁸ Community Research and Development Information Service, <https://cordis.europa.eu/project/id/785921/results>

3 Summary of testing and using DTOcean and DTOceanPlus

3.1 Use of DTOcean and DTOceanPlus in the EnFAIT Project

Within the EnFAIT project, the DTOcean and latterly DTOceanPlus tools are being used, both to inform the project and to further test and develop these open-source tools.

The assessment of the DTOcean and DTOceanPlus tools within the EnFAIT project was undertaken in five phases. These are summarised in Table 3.1, and use of the different software versions is shown schematically in Figure 3.1.

Table 3.1. Five phases of testing/assessing the DTOcean and DTOceanPlus tools within the EnFAIT project

| Test/assessment phase | Timescale | Reported in |
|---|--------------------|---|
| Initial assessment of the DTOcean tools (v1.0). | Oct. 17 – Dec. 18. | D10.3 Scenario Definition & Performance Metrics [16] and D10.4 DTOcean: Comparative with Design [17] |
| Detailed assessment of the DTOcean tools (v1.0 & v2.0) focusing on the five design stages. | Jan. 19 – June 20. | A series of 5 technical notes, shared with DTOceanPlus project, summarised in D10.5. |
| Review of functionalities proposed in DTOceanPlus and then preliminary testing of standalone development versions of modules. | Feb. 20 – Aug. 21 | Feedback was continually provided between the projects to improve the tool development and usability. |
| Final assessment, testing DTOceanPlus (mostly using integrated mode) to assess how well a small tidal array such as the EnFAIT project could be modelled. | Sept. 21 – Jun. 22 | D10.5 DTOcean: Comparative with Initial Predictions |
| Further use of the deployment design tools, plus Energy Capture in standalone mode, to provide guidance both for Nova and for the wider sector, on developing and optimising future arrays. | Sept. 21 – Dec. 22 | This deliverable, D10.6 DTOcean: Conclusion. |
| Updates to online documentation, based on lessons learnt in WP10 of EnFAIT | Jan. 23 – June 23 | DTOceanPlus online documentation |

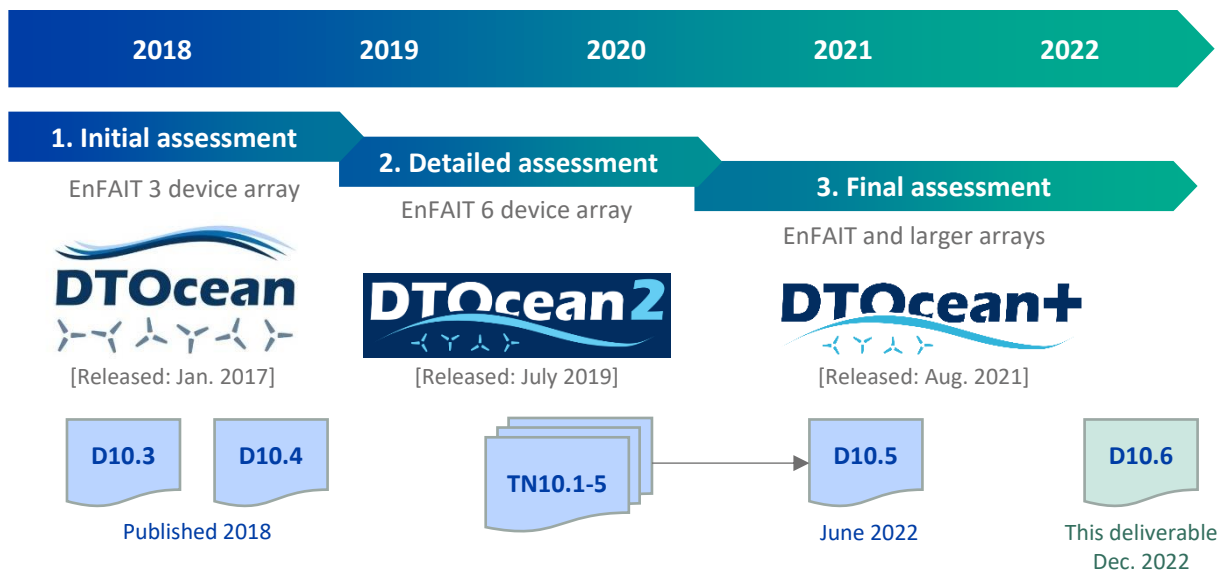


Figure 3.1. Schematic plan of assessments of DTOcean and DTOceanPlus within EnFAIT, including software release dates and related deliverables and technical notes produced.

It was found that the DTOcean tools had several limitations when trying to produce an optimal array layout for a small tidal scheme. Therefore, the decision was made to wait for the release of the DTOceanPlus suite of tools to perform the final assessment of the tools and comparison with the Nova Bluemull sound array.

While waiting for the release of the DTOceanPlus tools, the standalone post-beta development versions were tested within the EnFAIT project as far as possible. Additional feedback was provided to further improve the tools. Input was also provided to develop the documentation and training materials being prepared for the DTOceanPlus suite of tools, based on knowledge gained from using the DTOcean tools and their supporting documentation.

Due to the COVID-19 pandemic and subsequent related supply chain issues, the deployment of the final two turbines in the EnFAIT array was delayed. The assessment instead focused on how the results of DTOceanPlus compared with the expanded array of four turbines and the expected results from the six turbine EnFAIT array.

3.2 Summary of previous deliverables

This section briefly summarises the previous deliverables on testing DTOcean and DTOceanPlus within the EnFAIT project. The deliverable titles are as set out in the original description of work, however the scope of the work done at each stage of the project was adapted slightly, to reflect the development of the sector, and specifically, the DTOceanPlus tools that were developed in parallel with the EnFAIT project.

The other deliverables in WP10 are not summarised in this section, but this is how they fit within the work. The site and resource data collected were documented for the EnFAIT consortium in D10.2 Bluemull Sound Site Resource Map [18]. This data was used as an input to the DTOcean and DTOceanPlus modelling, as documented in D10.3 [16]. The related work by the Offshore Renewable Energy Catapult on the array interaction modelling also undertaken as part of WP10 is reported separately in deliverables D10.7–D10.10 [19]–[22].

3.2.1 D10.1 Data Requirements Definition & Collection Plan

Completed in November 2017, the first deliverable within work-package 10 set out data requirements and the plan for collecting the required data. It summarises the requirements for site data from the applicable IEC Technical Specification, 62600-201 ‘Marine energy - Wave, tidal and other water current converters - Part 201: Tidal energy resource assessment and characterization’.

The key data and the formats required for both the assessment of DTOcean and the array interaction modelling using MIKE21, were set out. This was followed by a plan for collecting the data. Publicly available data sources that could be used, if more detailed data were not available through the project, were also listed in D10.1.

3.2.2 D10.3 DTOcean: Scenario Definition & Performance Metrics

The first part of the assessment of DTOcean version 1 was presented in D10.3 in April 2018. This introduced the DTOcean tools. The scenario to be used in the assessment was then defined, in terms of the site location and bathymetry, the tidal timeseries from the hydrodynamic model and ADCP measurements, plus the Nova M100 turbine and other project information required for running DTOcean.

The assessment started with the first three DTOcean design themes, namely Hydrodynamic, Electrical, and Moorings & Foundations. For each, key parameters/results from DTOcean were compared with data from the EnFAIT array (turbines T1-T3), or a theoretical value where recorded data were not (yet)

available. Some results were normalised to the EnFAIT array value for commercial sensitivity reasons. Some comparisons with the real array were not possible given the limited data available. The similarity was classified as high, medium, low, or not applicable for each parameter, and an overall module ranking was assigned on a similar classification. The key points can be summarised as:

- The hydrodynamic metrics were overall ranked as medium similarity, although the calculation of AEP was a high similarity to the EnFAIT array.
- The electrical subsystem design scored a low similarity, as the design assumed an offshore substation with cables buried by cutting, whereas the EnFAIT array uses individual cables per turbine and seabed lay.
- The foundations module had high similarity for the device foundation type and mass required. However, a low similarity for suggesting a piled substation foundation rather than also using a gravity foundation, which is seen to be cost-effective for installation and decommissioning. Therefore the overall classification for the Foundations module was medium.
- Finally, the economic metrics calculated from these modules was ranked as high similarity.
- The main discrepancy highlighted in this first assessment was the requirement for an offshore substation, something that may be suited to larger arrays.

3.2.3 D10.4 DTOcean: Comparative with design

The second part of the assessment of DTOcean was reported within D10.4, in December 2018. This followed a similar approach, and considered the final two design themes, namely: Installation, and Operation & Maintenance, plus the three assessment tools of: Economics, Reliability, and Environmental. The scenario definition for the assessment was updated to reflect the inputs to these modules: requiring the outputs of the previous module, plus other data including the DTOcean Library of vessels, equipment, ports, and failure rates. The main findings were:

- Overall the installation was assessed as a medium similarity to the EnFAIT array, albeit with some parameters being very similar and others quite different.
- Major discrepancies between the module results and the real array were using multiple and more expensive vessels and equipment for the installation, and only using a single port for all operations rather than both nearby ports.
- There was insufficient information available to properly assess the O&M, Reliability and the Environmental modules.
- The Economics Assessment module was given a low similarity, due to an apparently non-standard method of discounting in the LCOE calculation.
- Within the reliability module, the overall system reliability output was highlighted as not improving after maintenance.

3.2.4 Technical notes on detailed assessment of DTOcean v1.0 and v2.0

Following D10.4, a detailed assessment was undertaken of the five design themes in DTOcean. During this exercise, version 2.0 of DTOcean was released, and was therefore used in the assessment process.

No deliverables were scheduled during the detailed assessment of DTOcean. Therefore, a series of five internal technical notes were produced covering this work. These addressed each of the five design themes:

1. Hydrodynamic module
2. Electrical module
3. Foundation module
4. Installation module
5. Operation & Maintenance module.

The technical notes provided recommendations to optimise the routines and tools of DTOcean, with directed feedback to improve the DTOceanPlus tools. It is noteworthy to mention that the technical notes aimed to highlight the limitations and areas for improvement for each module of the DTOcean tools, so these could be improved in the DTOceanPlus project which was running simultaneously. The technical notes were shared and discussed with the relevant organisations coding the DTOceanPlus tools. The key points of these technical notes were summarised within the appendix to D10.5.

3.2.5 D10.5 DTOcean: Comparative with initial predictions

Following the release of DTOceanPlus on 31 August 2021⁹, the integrated suite of tools was tested within EnFAIT. This only considered the Deployment and Assessment tools, as the State Gate and Structured Innovation tools were considered less relevant to the EnFAIT project.

The DTOceanPlus tools were assessed using a similar methodology to DTOcean described in D10.4. This involved testing various scenarios based on the EnFAIT array as well as other examples. The design methodology and results obtained from the tools were compared with those of the real array. Where data was not available, a comparison was made to expected results from other modelling. Some inputs were simplified due to data availability or because of limitations in the tools. A range of sensitivity analyses were also conducted on the input parameters to further explore the performance of the tools, especially where results were not as expected.

Both qualitative and quantitative assessments have been used for the assessment of the design tools. The complexity of these models, and in some cases lack of available data, mean it was not possible to perform a fully quantitative assessment. As part of the assessment, further enhancements to the DTOceanPlus tools have been suggested where limitations or errors were identified. This first addressed the overall suite of tools and their installation. Each module was then tested in sequence, providing a summary of the tool, comparison with the EnFAIT array, and any limitations or improvements identified. A tabulated list of 66 potential improvements to the DTOceanPlus tools was included as an appendix to the report.

3.3 Use of DTOceanPlus in Task 10.6

Beyond the final assessment of DTOceanPlus, further use and testing of the tools has continued in EnFAIT Task 10.6. This focused on the use of the Deployment Design tools, guidance on the use of which is elaborated in section 4.2. An assessment of electrical networks for ocean energy array was started, using the DTOceanPlus Energy Delivery tool in standalone mode. In addition, updates were made to the tools and documentation

3.3.1 Assessment of electrical networks for ocean energy arrays

Development of the DTOceanPlus Energy Delivery module was led by the University of Edinburgh, therefore it was of interest to use this to further study electrical networks for ocean energy arrays. Therefore a systematic parametric assessment of the various network options considered by the Energy Delivery module was undertaken. However, due to some limitations in the input data and calculation

⁹ Package v1.1.1 of the overall DTOceanPlus tools, but noting that each module has an individual version number

algorithm, the results from this work were inconclusive and require further investigation. It was possible to use the Energy Delivery tool programmatically using the API, to consider a wide range of input options; this is covered in more detail in section 4.2.9.

The electrical equipment costs used in the DTOceanPlus catalogue are based on a review conducted as part of the original DTOcean project [23]. This only considered cables at 6.6kV and above. No open-source compatible cost data was available in the DTOceanPlus project for lower voltages, primarily due to commercial sensitivities. Therefore, costs for 690V and 3.3kV cables taken to be the same cost as 6.6kV cables for an equivalent conductor cross-sectional area [24], an assumption that could be revised with additional cost data. Similarly, limited information was available on the costs for connectors and subsea hubs. In the electrical components catalogue, the cost for these does not vary with voltage.

The algorithm used in the electrical network optimisation does just that, it selects the lowest cost network option from the possible design space of the options chosen. While this is ideal for the base use case of designing optimised infrastructure, it limits the assessment of non-optimal designs. It was therefore not possible to perform an objective multi-parameter assessment of electrical network options, as initially intended.

It was also found that the outputs of any such assessment are very sensitive to the input assumptions made. In turn, these are sensitive to the specific details of a project/array being considered. There are also interdependencies between, e.g. the optimisation of the array layout for power capture, minimising costs of electrical infrastructure, and designing for installability and maintainability.

It may be possible to perform a simplified assessment of electrical networks, following a similar design logic to the Energy Delivery tool, but without the built-in optimisation, cable routing, and power-flow algorithms. This work is still ongoing; it will be reported in an academic journal publication if meaningful results are obtained.

3.3.2 Development of documentation and demonstration materials

Building on the assessment of DTOceanPlus in D10.5 [25], some sections of the online documentation were updated. This activity will continue within the remainder of the EnFAIT project, following the submission of this deliverable.

As an additional part of the ongoing use and demonstration of the DTOceanPlus tools, they were presented at a workshop at the International Network on Offshore Renewable Energy (INORE) symposium in Zarautz, Spain, held in October 2022 alongside the joint International Conference on Ocean Energy/Ocean Energy Europe conference in Donostia/San-Sebastián, Spain. For this demonstration, a generic tidal energy case study for the DTOceanPlus tools was developed within the EnFAIT project. This is now available through the DTOceanPlus documentation¹⁰. This work also involved testing updated versions of the tools, which resolved some of the bugs identified as part of the assessment of the DTOceanPlus tools in the EnFAIT project. At the INORE symposium, it was unfortunately found that the tools could not currently be installed on computers with the new Apple Silicon hardware. It was also confirmed that Windows 10 Home edition is not fully supported by Docker. These points will be clarified in the DTOceanPlus online documentation as part of the EnFAIT project.

¹⁰ https://gitlab.com/dtoceanplus/documentation/-/tree/master/sample_module_inputs

4 Guidance and lessons learnt

This section summarises lessons learnt from using the DTOcean and DTOceanPlus tools within the EnFAIT project. It provides further guidance on the use of the DTOceanPlus design tools. It also discusses future development and refinement of these open-source tools, building on the limitations and future improvements identified.

Some of this content has already been added to the DTOceanPlus documentation, and further updates will be made within the remainder of the EnFAIT project following the completion of this deliverable D10.6. This will make the online documentation more comprehensive, facilitating future use of the tools by a wider audience.

This section first covers the future development and optimisation of ocean energy arrays, with lessons from use of DTOcean and DTOceanPlus in the EnFAIT project.

4.1 Development and optimisation of future ocean energy arrays

The design of ocean energy arrays is a complex multi-faceted process with many, and often-conflicting, requirements. As originally highlighted in D9.7 [1], 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 4.1, noting this is far from exhaustive and these can often result in conflicting requirements. A simple example of a conflicting requirement could be the increased capital cost of a wet-mate electrical connector (compared to a dry-mate) versus the reduced time for installation and O&M activities. These requirements include both external constraints such as the location and resource, and design choices such as the turbine size, type of moorings/foundations, the electrical network layout, etc.

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 [26]. This is split into six stages of development, and nine evaluation areas of: Power Capture, Power Conversion, Controllability, Reliability, Survivability, Maintainability, Installability, Manufacturability, and Affordability.

Table 4.1. 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"> • Location(s) to be considered for array, highly influenced by the resource availability, other uses of the seas, and nearby infrastructure. • Type(s) of device to be used, e.g. 2-bladed horizontal axis tidal turbine. • Physical size of turbine and blades, rated power, cut-in/cut-out velocities, etc. • Whether on a floating platform or fixed to a structure or seabed, etc. • Location of the device in the water column. |
| 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 the device • Design of transmission/generator system(s), e.g. direct drive, gearbox, hydraulics, etc. • Type and design of moorings and/or foundations, shared or per device, how they will be installed and maintained, etc. |

| Theme | Parameters/notes/examples |
|---------------------------------------|---|
| Electrical connection to onshore grid | <ul style="list-style-type: none"> • Topology of intra-array network and export cable(s) to shore. • Voltage levels and requirements for transformers. • Balance between active and reactive power at the grid connection point. • Cable routes influenced by device positions, distance to onshore landing point, seabed type and bathymetry, current speeds, exclusion zones, etc. • Cable landing point constraints – one or multiple cables, landfall method, etc. • 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? • Use of quick connection systems (balance between CAPEX/OPEX costs). • Inspection/maintenance carried out in-situ, on a vessel, at port, etc. • Type and frequency of predictive/corrective maintenance regime used. • Types of vessels available, conditions they can operate in, distance to port, etc. |
| 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 e.g., 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 address, balancing real and perceived environmental risks against the need for renewable electricity and green jobs, etc. • Very important to consider, but beyond the scope of this report. |
| 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.

As the size of ocean energy arrays grow from the present status of a few turbines to larger commercial arrays with tens or hundreds of turbines, the complexity of this problem will increase further. Tools such as DTOceanPlus will be required to assist in this process. The availability of freely available open-source tools for the design and optimisation of ocean energy arrays can enable wider academic research that could contribute to innovations and cost reductions in the sector.

4.2 Using the DTOceanPlus design tools

While a summary of the DTOceanPlus tools is provided in section 2.2, this section covers their use in more detail, based on lessons learnt in the EnFAIT project. It is therefore primarily written from the perspective of designing an array of fixed tidal turbines, but it does touch on other functionalities. For more information on how to achieve specific tasks, please refer to the documentation for the individual modules¹¹.

¹¹ Available at <https://dtoceanplus.gitlab.io/documentation>

There are (generally) three levels of increasing complexity for each tool, referred to both as low/medium/high and 1/2/3. These are discussed below along with the varying data requirements. Using a lower complexity for an earlier module can impact on the level of calculation/results performed in later modules in the design chain, something to consider when using the tools. The array design is built up sequentially in subsequent modules, so any errors and uncertainties are propagated in the following design modules.

DTOceanPlus is typically used via a Main Module, which manages projects and studies, and provides the starting point for use of the other modules. A project within DTOceanPlus refers to a machine (either WEC or TEC) at a deployment site. Within this, several studies can be created to assess different options within the other design tools, such as array layouts, electrical architecture, or logistical solutions. These studies can then be 'forked' to consider changes only to the later modules in the design chain.

Once a project is set up in the Main Module, the next steps are to define and characterise both the deployment site and the device or machine to be used there. Next the 'energy chain' is designed and optimised: i.e. energy captured by the array of devices, transformed on board each device to electricity, and then delivered to shore via array and export cables. The last two design steps are the moorings and foundations, followed by consideration of logistical operations for the installation, O&M, and decommissioning phases of the array. There are then a set of four Assessment tools, focusing on different metrics: the array performance and energy yield; the economic perspective of lifetime costs; the reliability and other aspects; and lastly the environmental and social impacts. These assessment tools are fully aligned with the IEA-OES evaluation framework mentioned above [26]. There are also tools for structured innovation of new and improved concepts, and for stage gate assessment of technology development. This section focuses only on the use of the deployment design tools to design an array, not the assessment, structured innovation, or stage-gate tools.

Although the DTOceanPlus tools are modular and can be used independently, the key value is added by running the whole suite of integrated tools. This is done sequentially, as each module builds up the design. At present it is not possible to skip one or more modules in the design chain and have the user manually input the required information/results. In theory, it is possible to run a set of multiple modules all standalone and this could potentially skip one or more modules. In practice, however, formatting the data correctly and managing the API calls between modules will likely make this extremely difficult to achieve. This limitation could be addressed by future upgrades, building on the digital representation framework developed as part of the DTOceanPlus project [27]. This is partially implemented within the tools, but this would be a significant amount of development work to fully implement and test the complete functionality.

The following subsections cover use of the modules in turn. Section 4.2.9 then briefly discusses using the tools programmatically via the API, rather than by using the graphical interface.

As highlighted in the assessment of DTOceanPlus in D10.5 [25], differing coordinate systems are used in some of the modules. This has been clarified in the online documentation.

4.2.1 Main Module — setting up a project and study

The first step in using DTOceanPlus is to log in to the Main Module and create a new project, specifying a project name and selecting the technology to be considered (wave or tidal). Each project considers a single deployment site and type of device or machine. A previously used site or machine can be used by selecting this via the appropriate button. Alternatively, a new site and/or machine can be created at this point.

Once the site and machine are set, the user can create one or more studies; using the other tools to model and assess various options or configurations. Within these studies, there is the option to 'fork' the study,

and then as a new study, choose different options in one of the design modules. Modules prior to the fork are common to both modules. Changes after the fork only apply in that study but propagate to later modules within that fork.

There are currently no other data requirements for the main module.

4.2.2 Site Characterisation — defining and characterising the deployment site

Within DTOceanPlus Site Characterisation (SC), the parameters that do not vary over time, i.e. bathymetry, seabed roughness, and species presence, are referred to as “direct values”. Timeseries of the wind, waves, and currents are represented by a series of environmental conditions with a corresponding probability. These can either be 1D at a single point to represent the site, or 2D grids of points covering the site lease area and export cable corridor.

The Site Characterisation module includes nine reference sites with varying levels of wave and tidal energy (low, medium, high), as shown in Table 4.2. These can be used when the user does not have detailed site information. The user can also input any uniform depth instead of using the bathymetry data.

Table 4.2. Site Characterisation example sites (data from running SC)

| Wave resource mean/max Hs (m) | | | Current resource mean/max (m/s) | | | Site name/ location | Site centre coord. (°N, °E) | Lease area (km ²) | Water depth min/mean/max (m) | | |
|----------------------------------|------|-------|------------------------------------|------|------|------------------------|--------------------------------|----------------------------------|---------------------------------|------|------|
| Low | 0.48 | 3.14 | Low | 0.19 | 0.46 | Saint Briec | 46.60, -2.68 | 7.0 | 6.9 | 10.6 | 14.0 |
| Low | 1.27 | 5.79 | Med | 0.30 | 0.70 | Saint Nazaire | 47.10, -2.35 | 16.1 | 13.0 | 17.6 | 26.3 |
| Low | 1.01 | 5.85 | High | 0.48 | 1.1 | Calais | 50.80, 1.25 | 364.9 | 7.8 | 31.6 | 53.7 |
| Med | 0.95 | 5.21 | Low | 0.04 | 0.09 | West Groix | 47.77, -3.75 | 16.7 | 0.0 | 21.0 | 41.1 |
| Med | 1.32 | 6.87 | Med | 0.38 | 0.91 | Île de Ré | 46.10, -1.41 | 29.0 | 1.1 | 20.6 | 40.3 |
| Med | 1.32 | 7.21 | High | 1.43 | 3.33 | Raz Blanchard | 49.76, -2.00 | 101.9 | 0.0 | 49.5 | 86.0 |
| High | 1.84 | 11.79 | Low | 0.02 | 0.04 | Hossegor | 43.70, -1.58 | 195.7 | 19.1 | 108 | 471 |
| High | 1.67 | 10.39 | Med | 0.05 | 0.09 | Arcachon | 44.53, -1.34 | 60.3 | 3.5 | 32.3 | 46.4 |
| High | 1.39 | 9.40 | High | 1.69 | 3.96 | Fromveur | 48.44, -5.03 | 13.9 | 0.0 | 33.7 | 69.7 |

When creating a new site, the three levels of complexity are:

1. Choose a reference site, with 1D output parameters at a single point.
2. Choose a reference site, with 2D grid of output parameters across the site.
3. Input data files (1D or 2D) to describe a custom deployment site.

Summary statistics are then calculated and presented within the module; these are then used in subsequent modules.

To use the Site Characterisation module at complexity 3, the user must provide data on the site conditions, which is processed by the SC module.

- Geometry of the lease area and export cable corridor (as GIS shapefiles: .shp/.shx/.prj/.dbf), in degrees latitude, longitude to WGS84 spherical coordinates.
- Details of the seabed type, roughness, species, and bathymetry (all as NetCDF files¹²). Optionally, a constant depth can be used instead of uploading a bathymetry.
- Timeseries of environmental conditions of waves, tidal currents, winds, and water levels must be provided in 1D, i.e. varying in time at a single representative point on the site (in csv or NetCDF

¹² Network Common Data Form, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data. <https://www.unidata.ucar.edu/software/netcdf/>

format). Environmental conditions can optionally also be provided in 2D, varying both temporally and spatially.¹³.

Example geometries and timeseries are provided for a couple of sites. There are also default databases for the other parameters, see [28] for details. Unfortunately, these are very low resolution, at 0°00.25' (~450m) for French coastal waters and 0°05' (~9km) for the whole world, so are not particularly suitable for modelling tidal channels. Therefore the user should supply their own data wherever possible. This spatial resolution for species presence data can form a useful first step in assessing the potential environmental impacts at a site, although more detailed environmental surveys will obviously be required for a full assessment if not already available.

4.2.3 Machine Characterisation – defining the device

The Machine Characterisation (MC) module is used to input general parameters and dimensions that are used in subsequent design modules. These do not vary between complexity levels and are similar for wave and tidal devices.

A model is used to define the machine features related to power production, which has increasing detail with complexity level for each technology:

- Wave energy
 1. WEC archetype and capture width ratio (CWR).
 2. WEC archetype, average PTO damping and mooring stiffness, CWR or power matrix.
 3. Detailed WEC parameters, from which the linear potential theory coefficients are estimated using a BEM solver.
- Tidal energy
 1. Rotor power coefficient (C_p) and number of rotors
 2. Rotor power and thrust coefficients (C_p , C_t), number of rotors and distance between, cut-in and cut-out velocities.
 3. Matrix of C_p , C_t , number of rotors and distance between, cut-in and cut-out velocities, yaw angle or bi-directional option.

The level of complexity for the Energy Capture (EC) module is set by that of MC, as the MC model directly relates to the EC calculations.

The module also contains a default database with the RM1 and RM3 tidal and wave energy converters from the Reference Model Project [29], plus generic heaving cylinder and surging barge WECs.

Note that as the device electrical connector type and foundation type are set in Machine Characterisation, a separate project is required to consider alternative options for these parameters.

4.2.4 Energy Capture – calculate and optimise energy captured by the array of devices

The first step in the energy chain is the hydrodynamic energy captured by the device or array of devices. This module can either calculate results for a user specified layout, or it can calculate an optimised array layout of devices. The layout is specified in terms of UTM easting, northing projected coordinates, so care should be taken that these match the corresponding WGS84 coordinates from SC used to define the site, noting these are converted internally. Several array spacing options and optimisation routines are available within the tool, namely rectangular, staggered, and 4-parameter arrays, with either brute force, Monte Carlo, or CMA-ES optimisation.

¹³ Note that the spatial dimension is nominally 2D, but this is stored as a single dimension of node position in the NetCDF file.

The graphical interface for the Energy Capture model is the same at all complexities. The calculation depends on the model set in MC, with increasing accuracy associated with the more detailed inputs of higher complexity levels.

The outputs from the tool are the device positions (in the case of an optimised layout), the total annual energy captured by the whole array and by each device, plus a measure of the array interaction – the q-factor.

4.2.5 Energy Transformation — design energy transformation steps to electrical output

The energy transformation module is used to design the drivetrain and power conversion. It has three steps, each with independent levels of complexity. These have increasing data inputs and corresponding higher complexity calculations:

1. Based on rated power only.
2. Based on rated power and simple inputs.
3. Based on rated power, inputs, and detailed model.

The three energy transformation steps are:

- A. Mechanical transformation, considering:
 - i. direct drive or gearbox for tidal turbines, and
 - ii. air turbine, hydraulic, or linear to rotational motion system for wave energy convertors.
- B. Electrical transformation: either using a Squirrel Cage Induction Generator (SCIG), or a Permanent Magnet Synchronous Generator (PMSG).
- C. Grid conditioning.

The outputs from the tool are a bill of materials for the PTO, plus the energy/power at each step in the transformation for the whole array, each device, and each PTO (in the case of multiple PTOs per device).

4.2.6 Energy Delivery – design electrical infrastructure to transmit power to shore

The third and final step in the energy chain is to design the electrical infrastructure to deliver power to the shore. The Energy Delivery tool is technology agnostic between wave and tidal devices, although it does design umbilical cables for floating devices. The module only has two levels of complexity, with level 3 being the same inputs and calculations as level 2:

1. Simplified design with default options, always a radial network with collection point
2. More complex design with user inputs

The user specifies the cable landing point, optionally sets other parameters for the network, and chooses one of the six network types:

- Direct connection to shore for each device
- Radial connection with 1 or more strings of devices
- Radial connection with 1 or more strings of devices connected to a collection point
- Single cluster star
- Multiple cluster star
- Multiple cluster star, each connected to a transmission collection point

The collection point can either be a surface piercing substation where the voltage is increased, or a subsea hub with no voltage transformation. The cable routes and collection point locations are set by the optimisation algorithm. The user can choose the cable installation method, or the tool will calculate this based on the seabed type(s). Similarly, the tool will optimise the voltage(s) for the network, or the user can set these in the inputs.

At present, neither Energy Transformation nor Energy Delivery consider voltage transformation on the device. However, it is possible to manually select the device output voltage in ED. This will give a confirmatory warning that the on-board transformer is not designed.

If the export losses are too high, the tool may suggest the export voltage be increased. This can either be achieved by using a network with a collection point that can therefore incorporate a substation, and/or by adjusting the device output voltage as discussed above.

Cables and other equipment used is considered from the Electrical Components catalogue, and these can be updated as required if the user has more accurate information.

The Energy Delivery tool considers a series of design options and displays results for the top 3 ranked by cost of energy for the electrical components. Cost proxies are used for the costs of installing cables and collection points within the selection of the most cost-effective design, but these proxy costs are not included in the ED results as more accurate estimates are calculated in the LMO module.

The results from the tool are a bill of materials, layout of the cables and collection point(s), electrical losses, and real/reactive power delivered to shore.

4.2.7 Station Keeping — design moorings and foundations

The Station Keeping module is used to design the moorings or foundations for the devices and any collection points included in the design. For floating devices, it designs the mooring lines and anchors. This can also include the design of a 'master structure' – a rigid frame moored to the seabed to which multiple devices can then be moored. For fixed foundations, the module only considers the design of the foundation either gravity base or pile. It does not model any support structure such as a jacket. Note that the preferred foundation type is set within the machine characterisation module, and thus two projects are required to compare foundation types.

The three levels of complexity in the station keeping module relate to the detail of the user inputs, with dimensions for mooring system, anchors and foundations automatically determined for the lower complexity. The calculation is the same for each complexity.

When running in integrated mode, most of the inputs come from the previous modules and can be reviewed (but not edited) in the input pages. For the foundation design, the user can use default safety factors, load definition, and dimensions, or they can manually input these parameters.

Gravity base foundations can use concrete or steel, with a user defined density. These can either be rectangular, cylindrical, or 'contact points' which is a rotationally symmetrical 3-point frame of the required mass.

Piled foundations can either have an open or closed pile tip. At present, the user must manually input the length of pile (or height) above the seabed, as this is not automatically calculated. It should be set as the water depth plus freeboard required above mean water level.

Only an ultimate limit state (ULS) analysis is completed for fixed structures, with the 100-year return period wind, wave, and current data coming from the site characterisation module. For moorings, a failure limit state (FLS) analysis is also undertaken.

The outputs comprise a high-level bill of materials, estimate of the environmental impact, the design details, and results of the ULS/FLS assessment.

4.2.8 Logistics and Marine Operations — plans for installation, O&M, and decommissioning

Lastly, once the array design is complete, the Logistics and Marine Operations module can be used to plan the vessels, equipment, and ports used for the installation, O&M, and decommissioning. As with Energy Delivery, there are only two levels of complexity, with level 3 being the same inputs and calculations as level 2:

1. Simplified, with fewer and simplified inputs required
2. Full complexity

For both levels, the user can consider which of the three lifecycle phases to consider: installation, maintenance, and decommissioning (only in conjunction with installation, not separately). For the simplified mode, dates consider only the month, not the day, and some options take default values.

In integrated mode, the user should first add the project specific inputs, such as start dates, whether the device is repaired at port, is the device fully submerged, and if it is towed what draft is required. The inputs from the other modules should then be fetched in turn, or alternatively the user can upload these in the required json format. The site inputs are added by fetching the data from SC then clicking create to run some pre-processing. The project inputs can then be saved and locked, to progress to the next step of generating the installation and maintenance operations. The user can then specify requirements for each phase of operations, including entering a maximum distance to the ports for installation and maintenance. The methods to be considered for each operation should also be reviewed/specified. For projects with a piled foundation, the installation method should be selected, but this should be left blank if no piled foundations are used. Finally the scheduling of the operations is computed on the calculations page. On completion, the results show the operations plan and the scheduling thereof.

4.2.9 Using the DTOceanPlus tools via the API

The individual DTOceanPlus modules communicate via an application programming interface (API) over the hypertext transfer protocol (HTTP) using the OpenAPI specification. This means it is possible to interface directly with the ‘backend’ or ‘business logic’ that performs the design calculations from another piece of code or software. This allows for future development and expansion of the DTOceanPlus tools. It also permits batch running of an individual DTOceanPlus tool/module. This latter case was used within the assessment of electrical networks for ocean energy arrays discussed in section 3.3.1 The methodology of using the API is briefly discussed below, using examples from MathWorks MATLAB software, however similar code could be used in other programmes and languages.

The specifics of the API for each module are described within the API Reference section of that module’s documentation, noting that Each module is slightly different, resulting from the varied functionality and implementation. Most, however, follow a similar structure of collecting inputs, running the calculation, and returning the results. It is crucial to format the API request correctly, as not doing so will result in an error. The cause of data formatting errors is not always immediately clear as little feedback is given.

To better understand the API communication between the ‘frontend ‘ graphical interface and the backend, it is possible to use the browser’s developer console (or similar name) to monitor this. In Chrome press the F12 key or select More tools > Developer tools from the ⋮ menu in the top right. Then, click on the Network tab to view the HTTP requests between the frontend and backend as you use the DTOceanPlus module.

Within MATLAB, the `webread()` function¹⁴ can be used to read results using the API. Similarly, the `webwrite()` function¹⁵ can be used to add/update inputs or to run the calculation. These convert data stored in a MATLAB structure to the JSON format required by the API. For longer calculations it might be worth using the `http.RequestMessage` class¹⁶, as this can be set not to timeout. Brief code examples of these are shown below, but for full details of these functions refer to the documentation.

Box 4.1. Example MATLAB code to communicate with the Energy Delivery backend via OpenAPI

```
% check list of studies
studies_list = webread('http://ed.dtop.localhost/api/energy-deliv-studies/');

% Read in results for Energy Delivery study 2 into a structure ED.results
ED.id = 2;
url = sprintf('http://ed.dtop.localhost/api/energy-deliv-studies/%d/results', ED.id);
ED.results = webread(url);

% Create a structure with the updated device properties, in the format required for the API
ED.device.study_id = ED.id;
ED.device.technology = 'fixed';
ED.device.power = 250;
ED.device.voltage = 3300;
ED.device.connection = 'wet-mate';
ED.device.footprint_radius = 50;
ED.device.constant_power_factor = 1;
ED.device.connection_point = '(0,0,0)';
ED.device.equilibrium_draft = 0;

% Update the device inputs for study 2 in Energy Delivery by sending the structure to the API url
% using the PUT method to update
url = sprintf('http://ed.dtop.localhost/api/energy-deliv-studies/%d/inputs/device', ED.id);
response = webwrite(url, ED.device, ...
    weboptions('MediaType', 'application/json', 'RequestMethod', 'put'));

% Run the calculation with the updated inputs (300s timeout)
url = sprintf('http://ed.dtop.localhost/api/energy-deliv-studies/%d/results/calculate', ED.id);
response = webwrite(url, weboptions('MediaType', 'application/json', 'Timeout', 300));

% Alternative way to run the calculation, that will wait as needed (for longer calculations)
url = sprintf('http://ed.dtop.localhost/api/energy-deliv-studies/%d/results/calculate', ED.id);
import matlab.net.http.*
rq = RequestMessage(RequestMethod.POST, [ ...
    field.AcceptField('application/json, text/plain, */*') ...
    field.ConnectionField('keep-alive') ...
    field.ContentLengthField(0) ] );
response = rq.send(url);

% Add code as required to view results, or save to a structure, update other inputs, etc.
```

4.3 Future development of DTOceanPlus

The DTOceanPlus tools were released under an open-source license¹⁷ following the culmination of the EU funded DTOceanPlus project. The tools, along with their documentation and the source code, are hosted

¹⁴ <https://www.mathworks.com/help/releases/R2022b/matlab/ref/webread.html>

¹⁵ <https://www.mathworks.com/help/releases/R2022b/matlab/ref/webwrite.html>

¹⁶ <https://www.mathworks.com/help/releases/R2022b/matlab/ref/matlab.net.http.requestmessage-class.html>

¹⁷ GNU Affero General Public License v3.0 <https://choosealicense.com/licenses/agpl-3.0/>

on a public GitLab repository¹⁸. There it is possible for anyone to download the tools and source code, to review and understand the calculation processes that are carried out by the tools, and to suggest possible improvements to the code or log any bugs or issues with the tools. This section provides some guidance towards the continued future development of the DTOceanPlus suite of tools.

The open-source licence means that it is also possible to use the code (with appropriate attribution) in another open-source project. This was the case with DTOceanPlus, which built on the open-source codebase of the original DTOcean tools. The Logistics and Marine Operations tool is being further developed by WavEC Offshore Renewables within the EU-SCORES project¹⁹, and it is expected that improvements to the codebase will later be incorporated into the DTOceanPlus tools.

While anyone can get involved in the future development of the open-source tools, it is likely that at least some involvement of those responsible for the original development would be extremely beneficial. While the documentation of the DTOceanPlus code is comprehensive, there are still some gaps remaining.

4.3.1 Reporting potential errors, bugs, or improvements to the code

If a DTOceanPlus user finds a problem with the software, or they have a suggestion for a new feature or other improvement to the code, they can log this in the issues section of GitLab²⁰. The first step is to search existing issues, to check if a similar point has been raised before.

When reporting potential errors or bugs, there are good practice steps that should be followed, based on [30]. Remember that ‘open-source’ does not mean there is an obligation for the developers to fix any bugs identified. The more information you can give to help the developer, the more likely the error will be resolved in a timely manner.

1. Figure out the steps to reproduce a bug:
 - If you have precise steps to reproduce, this results in a useful bug report.
 - If you can reproduce occasionally, but not after following specific steps, you should try to provide additional information for the bug to be useful.
 - If you can't reproduce the problem, there's probably no use in reporting it, unless you provide unique information about its occurrence.
2. Enter a clear unique summary as the title, using approximately 10 words.
3. Write precise steps to reproduce. If a developer cannot reproduce the bug, it is unlikely to be fixed. If the steps are unclear, it might not even be possible to know whether the bug has been fixed. Try not to use vague language like just “it crashes” or “it doesn't work”.
 - Describe your method of interacting with DTOceanPlus in addition to the intent of each step. Be as explicit and verbose as possible, for example state whether you pressed enter or clicked a button after entering an input, as this might be part of the issue.
 - After your steps, precisely describe the observed (actual) result and the expected result. Try to clearly separate facts (observations) from speculations about what the cause might be. The latter may be helpful, but if not correct could waste time.
 - It may be appropriate to provide the inputs and/or outputs from previous modules to assist with debugging the error.
4. Providing additional information, such as the operating system you are using (e.g. Windows 10 Education, version 21H2), and the amount of free memory (RAM) available.

¹⁸ <https://gitlab.com/dtoceanplus>

¹⁹ European Scalable Offshore Renewable Energy Source <https://euscores.eu>, H2020 Grant agreement № 101036457.

²⁰ <https://gitlab.com/groups/dtoceanplus/-/issues>

The issues section can also be used to propose new features or other improvements to the software. Again, there is no obligation for any featured requested to be developed. Offering a more detailed proposal makes for a more impactful feature proposal.

The higher priority bugs and improvements identified within the detailed assessment of the DTOceanPlus tools have already been logged as issues within the GitLab. Where possible, further details or steps to reproduce any bugs are noted. Discussions with those responsible for the coding have worked towards resolving the most critical bugs already.

4.3.2 Technologies and architecture of the DTOceanPlus tools

There are a range of technologies that are used in the development of the DTOceanPlus tools. To facilitate future development of DTOceanPlus, these are summarised at a high level here, together with a description of the software architecture, based in part on [15], [31], [32]. The implementation for each module varies slightly, depending on the requirements of that module, and on the organisation that was responsible for its development.

The architecture of the DTOceanPlus suite of tools is modular; with the operation based on services. Each module has the following components:

- a backend business logic, which performs the calculations and design algorithms
- a frontend graphical user interface (GUI), accessed via a web browser
- an application programming interface (API), to allow communication between frontend and backend, and for communication between modules

DTOceanPlus uses the Docker Engine²¹, an open-source containerisation technology for building and running the DTOP modules within software containers. As noted in [33], “*a container is a standard unit of software that packages up code and all its dependencies so the application runs quickly and reliably from one computing environment to another*”. This allows the DTOceanPlus tools to be run on different operating systems and computer architectures. The final Docker production images for each of the modules are available in the Container Registry of the public GitLab repositories of DTOceanPlus. These are downloaded and set up by the DTOceanPlus installation script.

The main language for the implementation of the DTOceanPlus project is Python 3.x, which is used for the majority of the backend business logic. This is an upgrade from the (now obsolete) Python v2.x used in the original DTOcean (v1.0 & v2.0) tools. The backend logic for some modules builds on the backend from the original DTOcean code, upgraded to Python 3.x. For other modules, including all new modules, the backend was written from scratch.

The frontend graphical user interface for all modules uses the Element UI vue.js framework²² to provide the browser-based HTML pages to interact with the DTOceanPlus tools. The Flask framework is used to provide routing (pairing HTML to URL) to display information in different paths.

Each DTOceanPlus module provides a list of services that can be used by other modules. The services use the Representational State Transfer (REST) approach and HTTP as the transport protocol. The OpenAPI language is adopted to document the available API functionalities. The OpenAPI file (in JSON or YAML format) indicates all the paths, services and schemas provided to other modules. The API and its OpenAPI documentation are automatically generated from the data models of the BL using the SAFRS framework. The REST API for each module is public. For the orchestration of module services in DTOceanPlus (microservices) Docker in SWARM mode is used. Traefik proxy Edge Router interacts with Docker

²¹ <https://www.docker.com/>

²² Element UI <https://element.eleme.io/#/en-US>

registry/orchestrator API and generates the properly resolved routes to DTOceanPlus Module Services (microservices). These routes allow access to the Frontends and Backends of the DTOceanPlus modules, as interactive web applications for the users of DTOceanPlus. They can also be accessed directly using the API as discussed in section 4.2.9.

4.3.3 DTOceanPlus documentation

Again to facilitate future development of the DTOceanPlus documentation, the structure followed, and technologies used, are summarised here. As noted in [34] the documentation for DTOceanPlus follows an established system²³, is hosted alongside the code in the GitLab repository, and accessed via a web browser. It is split into four main areas for each module, preceded by a brief overview of the functionalities and workflow:

- **Tutorials** to give step-by-step instructions on using the tool for new Users.
- **How-to guides** that show how to achieve specific outcomes using the tool.
- An **explanation of features and calculation methods** gives technical background on how the tool works to give confidence in the tools.
- The **API reference section** documents the code of modules, classes, API, and GUI.

This can be visualised graphically as Figure 4.1. As explained in the documentation of the system [35] “... the characteristics of each quadrant of the documentation overlap with those of its neighbours in the scheme ...

- *tutorials and how-to guides are both concerned with **describing practical steps***
- *how-to guides and technical reference are both **what we need when we are at work, coding***
- *reference guides and explanation are both concerned with **theoretical knowledge***
- *tutorials and explanation are both **most useful when we are studying, rather than working***”

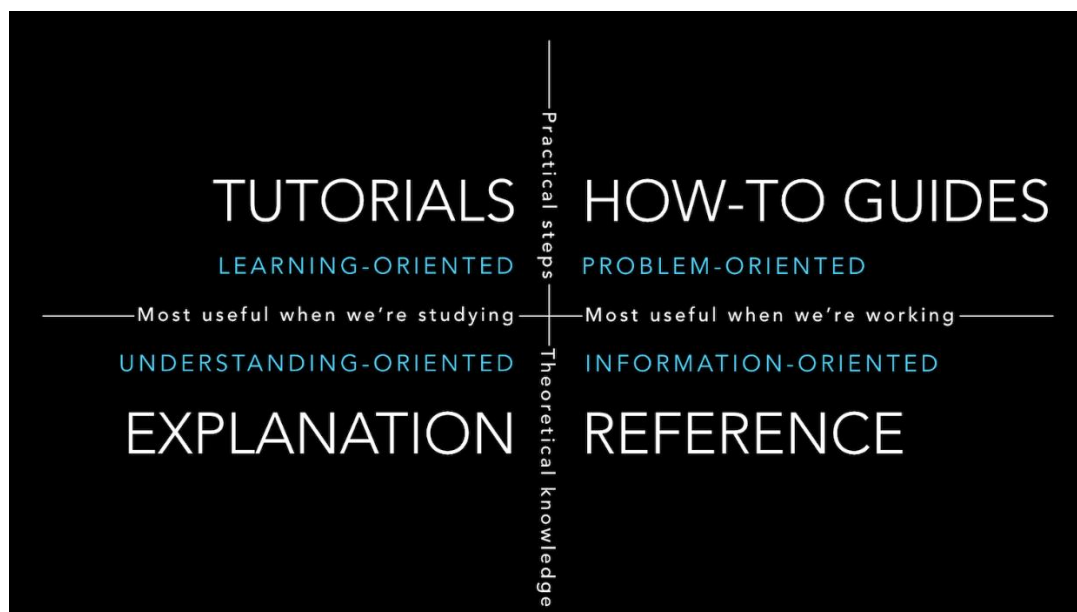


Figure 4.1: Schematic representation of the Documentation System [35]

The documentation is written in the reStructuredText (rst) format. This is a plain text format that is easy to write, readable and simple, yet powerful enough for non-trivial use. The files for the documentation are saved alongside the code for each module, within the /docs/ folder of that modules’ repository. The

²³ The Documentation System, <https://documentation.divio.com/>

autodoc and automodule packages, together with Python docstrings, are used to document the API reference section of each module, covering the OpenAPI description, the business logic, and the service layer.

The online documentation is produced using the Sphinx Python Documentation Generator²⁴, an open-source tool to produce “intelligent and beautiful documentation”. This creates a hyperlinked version of the complete documentation in HTML format, accessible via a web browser using GitLab pages²⁵. When this is built, the documentation for each module is copied into the overall documentation repository. The overall documentation covering the whole suite of tools, plus the Main Module and Catalogue Module, is saved within the DTOceanPlus documentation repository.

As previously noted, the documentation has been expanded within the scope of the EnFAIT project beyond what was possible in the DTOceanPlus project. Further updates will be made following the submission of this deliverable to incorporate the relevant findings and guidance from this work.

As with the main codebase, GitLab issues can be used to report errors, inconsistencies, or future improvements to the documentation.

²⁴ Sphinx Python Documentation Generator, <https://www.sphinx-doc.org/en/master/>

²⁵ DTOceanPlus Documentation, <https://dtoceanplus.gitlab.io/documentation/>

5 Conclusion and future work

The EnFAIT (Enabling Future Arrays in Tidal) project is demonstrating 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. Work Package 10 of the EnFAIT project seeks to validate and improve the first and second generation open-source design tools for ocean energy:

- **DTOcean** (Design Tools for Ocean Energy Arrays), and
- **DTOceanPlus** (Advanced Design Tools for Ocean Energy Systems Innovation, Development, and Deployment).

The work in WP10 has delivered a comprehensive assessment of both the DTOcean and DTOceanPlus tools, using Nova's Shetland Tidal Array as a case study, based on experience gained during the EnFAIT project. It has also significantly improved the online documentation of the DTOceanPlus tools.

DTOcean is a suite of open-source design tools for ocean energy, originally released in 2017. It offers a holistic assessment of the multi-faceted process of optimising the layout of arrays of wave and tidal energy converters. The original DTOcean tools (v1.0 & v2.0) are more focussed on the design of larger commercial-scale arrays, which is not yet aligned with the status of the sector. For example, the electrical network design always assumed an offshore substation. Therefore, it is not possible to accurately model or assess a small tidal array such as EnFAIT. There is also the issue with these tools using now outdated software (Python 2 and PyQt4), as noted in D10.5 [25].

The **DTOceanPlus** tools build on the strong foundation of DTOcean, with a second-generation of open-source design tools for ocean energy released in August 2021. These new tools address some of the limitations of DTOcean, and it is now possible to represent the design of a small tidal array such as EnFAIT. Not all results matched the experience of Nova, however. Costs estimates using the defaults of the tools were typically significantly higher than the experience within EnFAIT, although most of these can be edited and updated within the tools and supporting catalogues. Some of the design decisions also differed, for example the DTOceanPlus tools using specialised vessels with significantly higher costs and always requiring an ROV or divers to monitor installation operations.

The DTOceanPlus tools offer strong potential for planning future arrays of wave and tidal energy, along with supporting the development of these technologies. Currently, there are several aspects of the tools that require adjustment in order to fulfil this potential. The work within WP10 of the EnFAIT project has provided a significant amount of testing of the tools, allowing any potential limitations to be identified and then documented. This work is instrumental in facilitating future fixes and improvements.

The assessments of both DTOcean and DTOceanPlus within the EnFAIT project identified bugs, limitations, and potential areas for future development of these tools. Due to the close collaborative working between the two projects, many of the limitations identified in DTOcean and the initial assessment of DTOceanPlus were resolved and/or incorporated into the DTOceanPlus tools.

Discussions with those involved with the DTOceanPlus software development were held, to prioritise improvements and work towards resolving them. Some of the more critical issues identified in the final assessment of DTOceanPlus following the release of the tools have also now been fixed. To facilitate further future refinement and development of the DTOceanPlus tools, the limitations and potential improvements identified within the EnFAIT assessment have been logged as issues on the DTOceanPlus tool's GitLab repository, as is standard for this type of open-source project.

In addition, to make the DTOceanPlus tools easier to use, the overall documentation for DTOceanPlus is also being revised within the EnFAIT project to clarify sections that were less clear and further improve

their usability. The documentation has already been significantly updated, and content from this final deliverable will be incorporated into the documentation before the end of the EnFAIT project.

Discussions will also continue with the DTOceanPlus developers around the possible resolution of issues and improvements identified. Finally, further explorations of the possible electrical infrastructure for future arrays will continue within the EnFAIT project WP10. As noted, any significant findings will be published in an academic journal as appropriate.

Within the rest of the EnFAIT project, the final two turbines (T5 and T6) are being deployed in the Shetland Tidal Array (six turbines total). The turbines will, as per the original plan, continue to be operated and moved to add to the already large volume of intra-array flow data and yield measurements. This real-world tidal array data will be used to validate the final array interaction modelling work which will be reported in D10.9 and D10.10.

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