



EnFAIT



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ENFAIT ENABLING FUTURE ARRAYS IN TIDAL

DTOcean: Comparative with Initial Predictions



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NOVA
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IDEA

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CATAPULT
Offshore Renewable Energy

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Abbreviations and Definitions

AEP	Annual Energy Production
API	Application Programming Interface
CAPEX	Capital Expenditure
CF	Capacity Factor
CfD	Contracts for Difference
CP	Collection Point
DoE	US Department of Energy
DP	Dynamic Positioning
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
HDD	Horizontal Directional Drilling
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LMO	Logistics and Marine Operations (DTOceanPlus module)
MC	Machine Characterisation (DTOceanPlus module)
MM	Main Module (DTOceanPlus module)
MTTF	Mean Time To Failure
NaN	Not a Number
NPV	Net Present Value
O&M	Operation and Maintenance
OEC	Ocean Energy Convertors
OLP	Onshore Landing Point
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)
RMP	Reference Model Project
SC	Site Characterisation (DTOceanPlus module)
SCIG	Squirrel-Cage Induction Generator
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 sets out the lessons learned from the application of both the DTOcean and DTOceanPlus tools to model the real-world Nova tidal turbine array. It is to be submitted to satisfy deliverable D10.5 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 2.2.1 after the description of the tools). Feedback from using the tools in the EnFAIT project has already informed the design of DTOceanPlus; it will also help identify and guide future improvements to the DTOceanPlus tools and documentation.

This deliverable (D10.5) continues the work done in D10.3 DTOcean: Scenario Definition & Performance Metrics, and D10.4 DTOcean: Comparative with Design, which between them covered the first assessment of the capabilities of the DTOcean model for the EnFAIT project. D10.5 presents both the more detailed assessment of DTOcean (v1.0 & v2.0), and the subsequent final assessment, of the capabilities of the DTOceanPlus suite of tools. Further results and findings from using DTOceanPlus to model future arrays will be reported in D10.6 DTOcean: Conclusion, due to be completed in Dec. 2022.

This deliverable focuses on the assessment of the most recent design tools, the DTOceanPlus suite released in August 2021. The detailed assessment of DTOcean undertaken in 2019-20 is provided in Appendix B for completeness. The assessment process involved reviewing the capabilities of the design tools (both DTOcean and DTOceanPlus) to accurately model a small tidal array, such as the EnFAIT project. During the assessment, a series of limitations of – and potential improvements to – the DTOceanPlus tools were identified. The work done to date and planned over the coming months on refining and improving these design tools and their associated documentation is also summarised.

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, 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 first introduces and summarises the capabilities of DTOcean and DTOceanPlus, open-source design tools used for the optimisation of array design. It then describes how these tools are used in WP10 of the EnFAIT project.
- Section 3 defines the data sources and scenarios used in the assessment of the DTOcean and DTOceanPlus tools, including a description of the EnFAIT array.
- Section 4 introduces the assessment of the suite of DTOceanPlus design and assessment tools, covering the methodology and discussion on the overall suite of tools.
- Section 5 covers the assessment of each of the DTOceanPlus Design and Assessment modules.
- Section 6 then provides overall findings from the assessment of DTOceanPlus.
- Section 7 offers conclusions and lessons learned from the testing of DTOcean and DTOceanPlus tools compared to the design of a real-world array, plus summarises next steps and future work.
- This is supported by two appendices:
 - Appendix A collates the potential future improvements to the DTOceanPlus tools identified as part of the assessment within EnFAIT.
 - Appendix B outlines the historical assessments of the DTOcean tools, first recapping the previously reported assessments, then covering the detailed assessment of each of the five design stages, before providing an overall assessment of the tools.

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 this to calculate results. 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 supported³ [7].

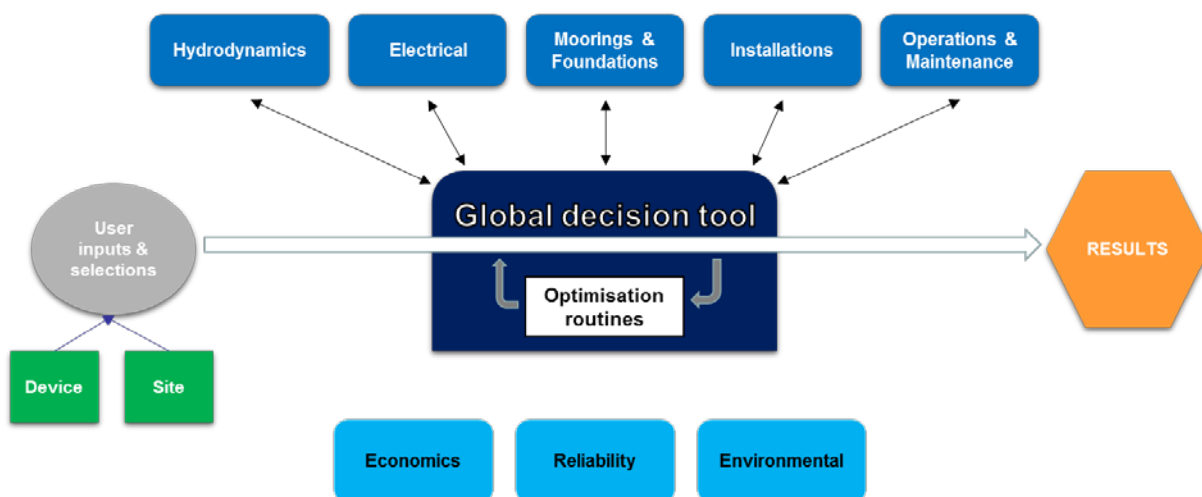


Figure 2.1. Schematic structure of DTOcean tools [8]. Applies to both v1.0 & v2.0.

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 2nd generation design-tools for the selection, development, and deployment 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.

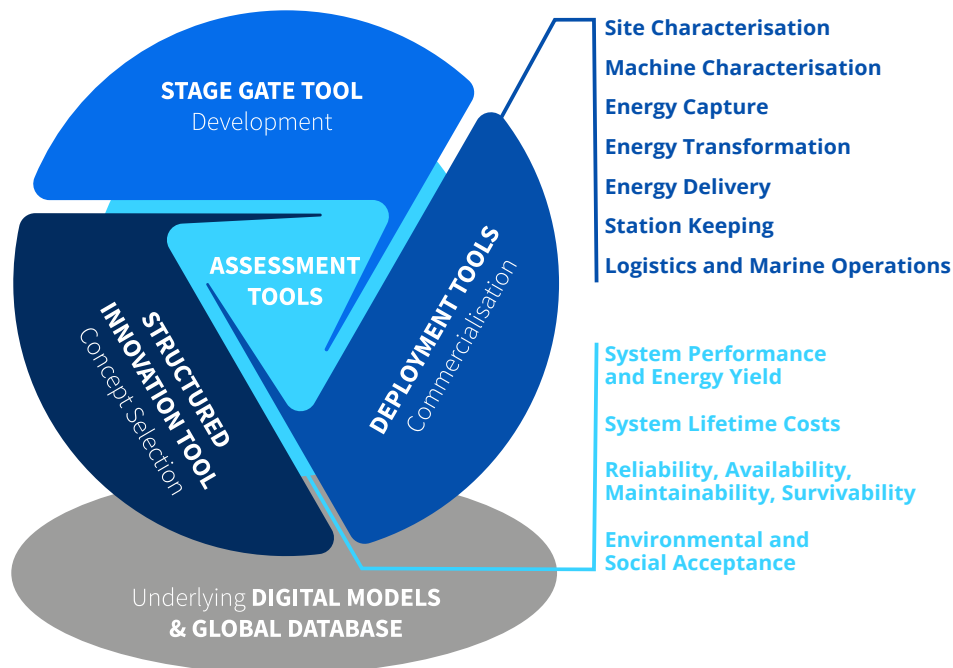


Figure 2.2. Schematic showing main DTOceanPlus tools [10].

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

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

[†] New tools in DTOceanPlus. These tools are 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.

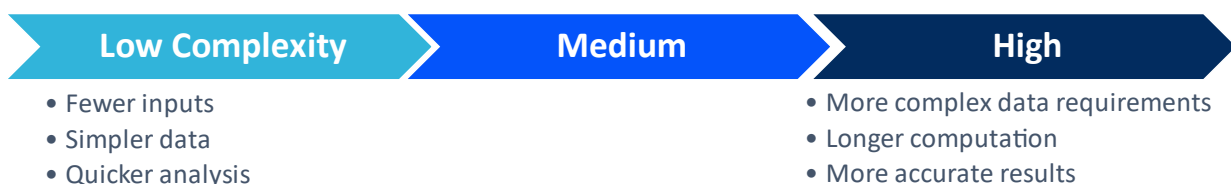


Figure 2.3. Levels of complexity within DTOceanPlus [10].

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.

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.

2.2.1 Documentation

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.

2.2.2 Coordinate systems and direction conventions

Differing conventions can be used to define coordinate systems and direction conventions for bathymetry and environmental conditions (winds, waves, and tidal currents). For clarity, and as a precursor to the assessment, those used in DTOceanPlus are summarised below. This is not presently fully described in overall DTOceanPlus documentation, and so this will be updated as part of the EnFAIT project.

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>

There are various ways to represent **horizontal positions** on the Earth's surface, with two common standards used by DTOceanPlus modules:

- *World Geodetic System 1984* (WGS84) specifies the latitude and longitude coordinates as degrees north and degrees east. These are given as decimal degrees (1.2345°), with south of the equator and west of the prime meridian negative. Note that these may be specified elsewhere as degrees, minutes, and seconds of arc (e.g. $1^\circ 15' 4.2''$). The satellite global positioning system (GPS) uses WGS84 coordinates.
- *Universal Transverse Mercator* (UTM) is a grid projection, with coordinates specified in meters east and meters north for 6° wide zones around the Earth either side of the equator. Most of the UK fits within zone 30N, although the Outer Hebrides and Ireland are in zone 29N, and East Anglia and much of the North Sea are in zone 31N. To avoid negative coordinates, the central meridian of the zone is defined as 500,000m east. The equator is 0m for the northern hemisphere zones.

The Ordnance Survey National Grid (OS NG) is also used in the UK, which is similar to UTM and overlaps with UTM zones 29–31. However, it has different origins and a slightly different scale factor, see [16] for further details. Other countries and regions have different local coordinate systems.

The modules considering the site bathymetry (EC, ED, SK) all use UTM coordinates for their calculations. This allows simplified rectangular grids, with little discrepancy over the scope of a site. The modules with a broader spatial coverage (SC, LMO, ESA) all use WGS84, as the curvature of the Earth's surface becomes more important at larger scales. It is possible to directly convert between coordinate systems with an acceptably high degree of accuracy, but all approximate the true shape of and position on the Earth. There also appears to be some discrepancy in the foundation coordinates output in SK compared with device positions in EC, as discussed in section 5.8.

Vertical distance can be measured relative to any datum, nominally mean sea level. A timeseries can be added to represent the tide level relative to this, optionally accounting for an offset to a country, local, or chart datum. The convention within Site Characterisation is that depths are positive (into the ocean). However, Energy Delivery and Station Keeping use the opposite, with a negative z-coordinate (i.e. upwards positive).

Waves are specified in terms of significant wave height H_s and peak period T_p , with directions described using degrees in a 'coming-from' convention.

Current velocities are specified in m/s, with directions described using degrees in a 'going-to' convention. For some cases, the eastwards and northwards u, v components are used.

Wind speeds are measured in m/s at a reference height of 10m, and as with waves, the direction uses a 'coming-from' convention.

2.3 Use of DTOcean and DTOceanPlus in the EnFAIT Project and overall methodology for assessments

Within the EnFAIT project, the DTOcean and DTOceanPlus tools are being used, both to inform the project and to further test and develop these open-source tools. The five-phase assessment of the DTOcean and DTOceanPlus tools within the EnFAIT project is summarised in Table 2.3, and use of the different versions is shown schematically in Figure 2.4.

Testing of DTOcean within EnFAIT started in September 2017 with version 1.0, which had been released in January 2017. After the release of DTOcean version 2.0 in July 2019, the detailed assessment considered both versions in parallel. The assessment of DTOcean is summarised in Appendix B.

Following the assessment of DTOcean, the proposals for DTOceanPlus were reviewed and preliminary versions of the tools tested within the EnFAIT project. Feedback was offered to improve the tools.

The final assessment within EnFAIT followed the release of DTOceanPlus in August 2021. This used the DTOceanPlus Design and Assessment tools (in integrated mode where possible). Further use of the DTOceanPlus tools is ongoing to provide recommendations on future arrays, focusing on array layouts in Energy Capture, electrical networks using Energy Delivery, and logistical operations using LMO.

Table 2.3. 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 [17] and D10.4 [18]
Detailed assessment of the DTOcean tools (v1.0 & v2.0) focusing on five design stages.	Jan. 19 – June 20.	A series of 5 technical notes, shared with DTOceanPlus project. These are summarised in Appendix B.2.
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	This deliverable, D10.5.
Further use of Energy Capture, Energy Delivery, and Logistics & Marine Operations tools in standalone mode to provide recommendations both for Nova and for the wider sector for future arrays.	Sept. 21 – Dec. 22	D10.6 DTOcean: Conclusion, due to be completed Dec. 2022.

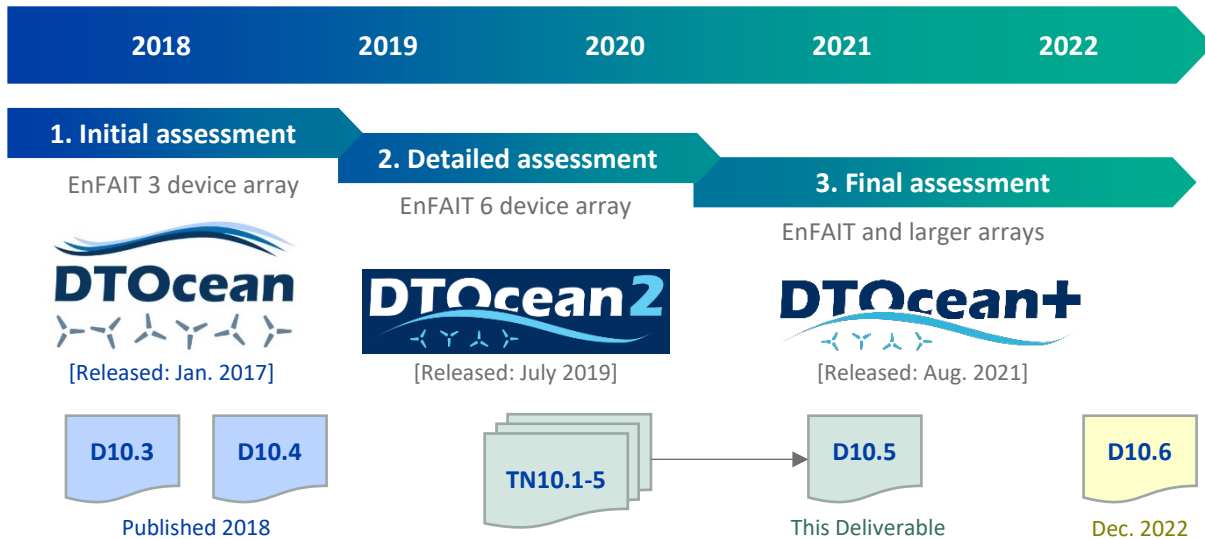


Figure 2.4. Schematic plan of assessments of DTOcean and DTOceanPlus within EnFAIT, including software release dates and related deliverables and technical notes produced.

The initial assessment of the DTOcean tools focused on the first three design themes (Hydrodynamic, Electrical and Foundation). This was reported in D10.3 DTOcean: Scenario Definition & Performance Metrics [17]. The assessment of the final two design themes (Installation and Operation and Maintenance (O&M)) and the three assessments (Economics, Reliability, and Environmental) along with an overall assessment was reported in D10.4 DTOcean: Comparative with Design [18]. These two deliverables are summarised in appendix B.1. Subsequently, a series of internal technical notes were

produced with a more detailed assessment of the five DTOcean design stages; these are summarised in appendix B.2. The overall assessment of DTOcean is given in appendix B.3.

Feedback from the use of DTOcean within the EnFAIT project was shared with the coders of the DTOceanPlus tools to assist in their development. This included the detailed assessment technical notes and bilateral calls with the developers of the DTOceanPlus tools to facilitate discussions.

As noted in appendix B.3, 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. This stage of feedback is not reported in detail, as it was largely implemented within the timeframe of the DTOceanPlus project.

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. Some issues were encountered with a few of the modules, as discussed in sections 4 and 5. Therefore the focus within the EnFAIT project was directed towards three modules of particular interest, namely Energy Capture, Energy Delivery, and Logistics & Marine Operations.

The overall methodology applied to assess the DTOcean and DTOceanPlus design tools within the EnFAIT project involved testing various scenarios based on the EnFAIT array and other examples, as discussed in section 3. 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 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. Discussions are ongoing with the partners of the DTOceanPlus project regarding future updates to the tools to address these.

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

3 Data sources and scenario definition

This section summarises the data sources and scenarios used in the assessments of both DTOcean and DTOceanPlus. Firstly, a description of the Shetland Tidal Array, also referred to as the EnFAIT array, then the scenarios used in each stage of the assessment are prescribed.

As well as information from Nova Innovation regarding their turbines and the EnFAIT array, the relevant internal data sources from the DTOcean and DTOceanPlus tools were utilised during the assessment. As noted in sections 2.1 and 2.2, the tools are supported respectively by a database and catalogues. These both contain reference component data such as electrical cables and connectors, plus vessels, ports etc. For both DTOcean and DTOceanPlus the Culivoe Harbour and Belmont Slip ports used within EnFAIT were added, as these were not included by default.

3.1 The EnFAIT array

3.1.1 Site location and array layouts

The EnFAIT tidal array will consist of six 100kW tidal stream turbines, deployed in several stages in the Bluemull Sound, Shetland, see Table 3.1. The Bluemull Sound is situated between the Shetland Islands of Yell and Unst. The site for the array is east of the Ness of Cullivoe, as shown in Figure 3.1. It is close to Culivoe Harbour on Yell and not far from Belmont Slip on Unst.

The array comprises three Nova M100 turbines (T1-T3) and three Nova M100-D turbines (T4-T6), more details of these in the following section. The turbines are situated in water of around 30-40m depth. The first four turbines (T1-T4) all have individual export cables to shore, routes for T1-T3 shown in Figure 3.2. The final two turbines (T5 & T6) will be connected via subsea hub, with a common export cable to shore.

Table 3.1. Turbines in the EnFAIT array, with installation dates and connection type.

Turbine	Model	Installation date	Electrical connection
T1	M100	Spring 2016	Individual cable to shore
T2	M100	Summer 2016	
T3	M100	Summer 2017	
T4	M100-D	Summer 2020	
T5	M100-D	Autumn 2022	Connected to subsea hub
T6	M100-D		



Figure 3.1. Bluemull Sound location. (Source: Google Earth)

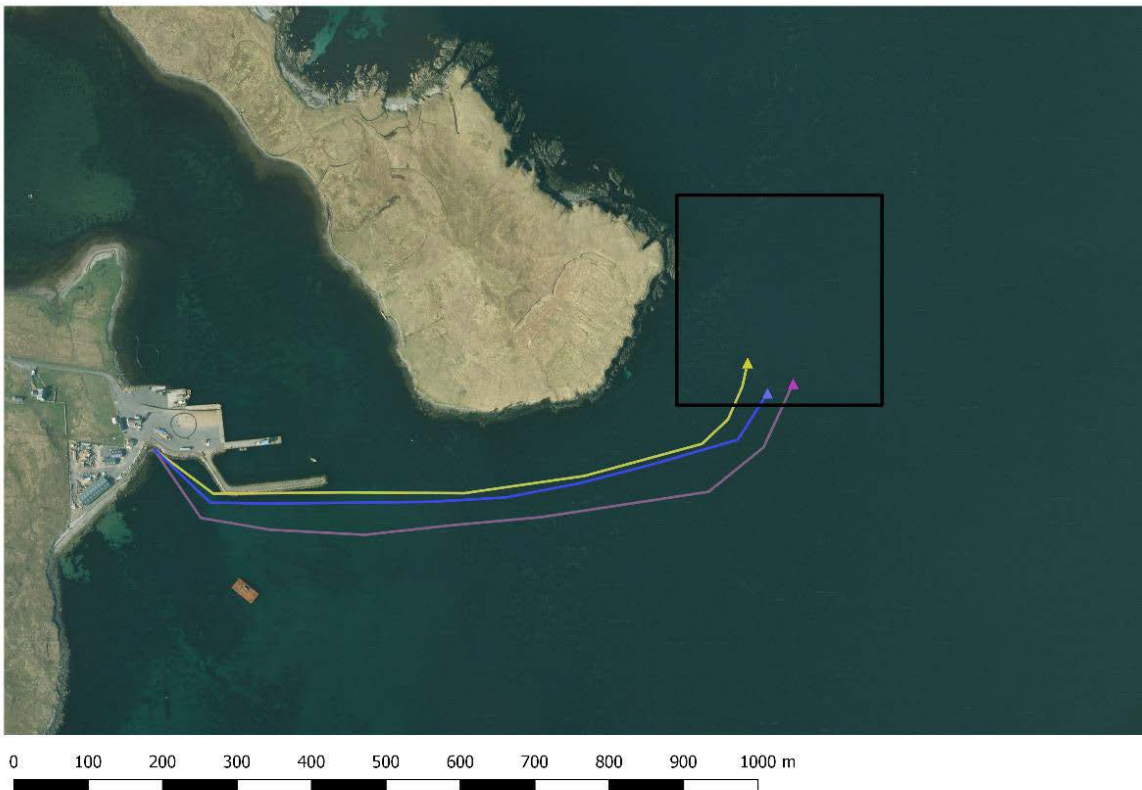


Figure 3.2. Shetland Tidal Array location east of Cullivoe Pier, lease area shown by rectangle, T1-T3 turbine locations and cable routes also shown.

Within the EnFAIT project it is planned to initially deploy the six turbines in two rows of three turbines. The array will then be reconfigured to study the effects of array interaction, with the northern three turbines moved closer to the southern row, as shown in Figure 3.3. Note that the layouts tested were initial proposals, the final deployment locations will vary slightly. These layouts are also referred to as large and close array spacing in the assessment of DTOcean.

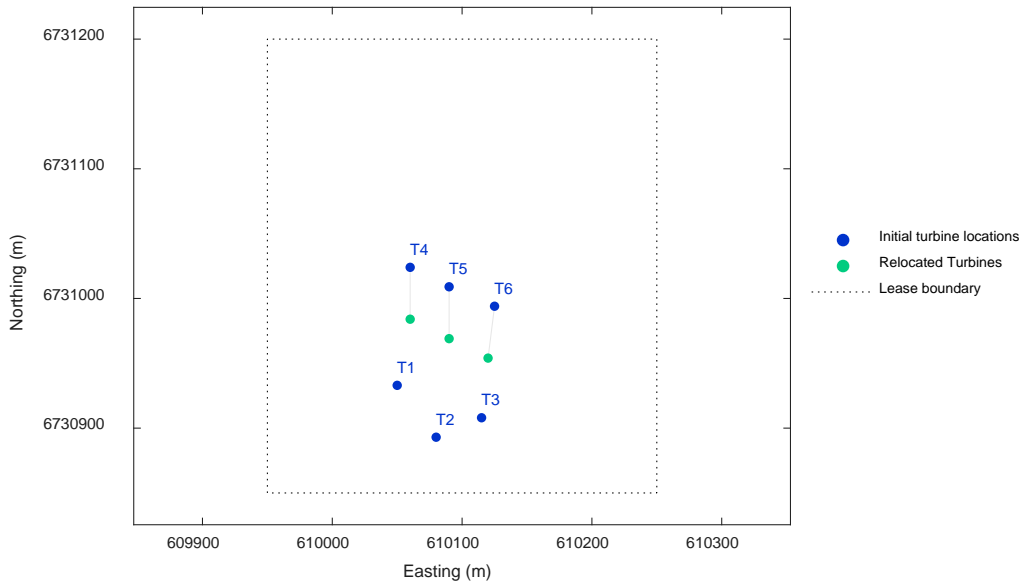


Figure 3.3. Initial and reconfigured EnFAIT array layouts (2018 proposals).

3.1.2 Nova M100 and M100-D turbines

Both the Nova M100 and M100-D turbines are 100kW bottom mounted, gravity anchored, non-yawing, horizontal-axis tidal turbines. Each tidal turbine comprises a cylindrical nacelle unit, rotor, and gravity base with ballast weights to secure it to the seabed (no seabed drilling or additional site works are required).

The M100-D is a later evolution with a direct-drive generator removing the need for a gearbox. The Nova M100-D was developed in the EU H2020 D2T2 project to cut tidal LCOE by 30% through much improved efficiencies (full and part-load), high reliability (significantly fewer components) and longer periods between maintenance (>2 years).

Table 3.2. Turbine technical specifications (Typical configuration: can be adjusted to optimise performance at a particular site)

	M100	M100-D
Rated capacity (kW)	100	100
Design life (years)	20	20
Blade diameter (m)	9.0	8.5
Hub height (m)	9.0	8.9
Rotor speed (rpm)	10–25	10–27
Tidal speed range (m/s)	0.7–3.0	0.5–6.0
Tidal speed for rated power (m/s)	2.2	2.0
Drivetrain	Gearbox	Direct drive



Figure 3.4. Nova Innovation M100 Tidal Turbine at Belmont, showing rotor blades in blue, cylindrical nacelle in white, and gravity base in orange.



Figure 3.5. Nova Innovation M100-D Tidal Turbine, showing rotor in blue, cylindrical nacelle in white, and gravity base in orange. Lifting frame shown on right.

3.1.3 Environmental data

A tidal flow model has been built within EnFAIT by OREC using the MIKE 21 2D modelling package to give flow information for the extent of Bluemull Sound. This model used regional bathymetry and coastline data from various high-resolution databases to represent the physical aspects of the site. It has been calibrated against recorded site data from various acoustic Doppler current profiler (ADCP) deployments. The model also considered the wave conditions, utilising recorded operational wave criteria from different locations in Bluemull Sound. The output from this flow model for the year 2018 was used as an input for DTOcean and DTOceanPlus.

Detailed bathymetry data is available, covering an area of the Bluemull Sound larger than the array lease area and cable corridor. This was used at a 5m resolution within the assessments, although sensitivity analyses to data resolution were also conducted.

3.2 Scenarios considered for each stage of assessment

Initial and detailed assessments – DTOcean

The initial assessment of DTOcean (conducted in 2018) considered the EnFAIT array with turbines T1-T3 installed. At this stage in the project, some results from the real array were not available, and the output from DTOcean was compared against other predictions.

The detailed assessment of DTOcean (v1.0 & v2.0, conducted 2019-20) was compared against the full six turbine array, with three cases:

- 1) Nova Innovation Design 1 (large array spacing), the proposed initial placement of the six turbine EnFAIT array.
- 2) Nova Innovation Design 2 (close array spacing), the proposed relocated placement of T4-T6 that will be used to study the array interaction.
- 3) DTOcean Optimum Design – using the optimisation routine of DTOcean to propose an array layout for six turbines at the Bluemull Sound site.

These three layouts were then assessed in the other design stages.

Final assessment – DTOceanPlus

The final assessment within EnFAIT (conducted 2021-21) used the DTOceanPlus tools. This considered the EnFAIT array at different stages, with 3, 4, and 6 turbines installed, using both layouts 1) and 2) above. The optimisation routes of DTOceanPlus were also tested to produce suggested layouts with varying numbers of turbines.

As well as modelling the Nova EnFAIT array, a 50-device array using the RM1 tidal stream turbine from the US Department of Energy Reference Model Project [19] was tested to provide another study case. As this is not a real array, no comparison of the results was performed. It was only used to provide a wider scope of testing, to understand the strengths and limitations of DTOceanPlus, by modelling another tidal array at a different scale.

4 Assessment of DTOceanPlus Design and Assessment tools

This section introduces the final assessment within EnFAIT, of the suite of DTOceanPlus Design and Assessment tools. It considers ease of use and how well these tools can model a small tidal array such as the EnFAIT project. Some findings from the demonstration of the tools within the DTOceanPlus project using Nova’s EnFAIT array [14] are repeated in this assessment for completeness.

As mentioned in section 2.2, it is noted that further testing and development of the DTOceanPlus tools was anticipated after their initial release in August 2021. The extensive testing performed in the EnFAIT project will help identify and document any bugs and limitations, facilitating future development and refinement of the suite of tools.

4.1 Assessment methodology and use of DTOceanPlus tools

The assessment of the DTOceanPlus tools¹⁰ focused on using the Design and Assessment tools sequentially in ‘integrated’ mode. Some testing was also undertaken in ‘standalone’ mode for most modules, although this generally did not form part of the assessment. As each of the modules must be run sequentially in integrated mode, it has not been possible to test some of the later modules in as much detail because of time spent resolving issues in earlier modules.

Limitations were found with some of the modules, and these affected other modules of particular interest to Nova. More detailed testing and evaluation is therefore being conducted in standalone mode for the Energy Capture, Energy Delivery, and Logistics & Marine Operations tools. As discussed in section 2.2, when using the tools in standalone mode, the user needs to provide all the input data that would normally be the output of previous tools. While this adds complexity, it offers more flexibility and control of the scenarios tested.

A summary of the main cases tested in each DTOceanPlus module for the final assessment in EnFAIT is provided in Table 4.1. This also shows the scenario/data used in subsequent modules when used in the integrated mode.

Table 4.1. Summary of test cases for assessment of DTOceanPlus. Use of data in subsequent modules in integrated mode shown by arrows, ↓ data only used for testing, ↓ data used for assessment of tools.

Module	Summary of cases tested & data flow	Mode assessed
Main Module	<ul style="list-style-type: none"> Used to manage project/study in all tools 	Integrated
Catalogues	<ul style="list-style-type: none"> Used to provided data to other modules ↓↓ 	Integrated
Site Characterisation	<ul style="list-style-type: none"> Bluemull site data ↓ Built-in example sites ↓ 	Integrated
Machine Characterisation	<ul style="list-style-type: none"> Nova M100 & Nova M100-D turbine specifications ↓ Generic & RM1 turbine specifications ↓ 	Integrated
Energy Capture	<ul style="list-style-type: none"> EnFAIT site layouts with 3, 4 & 6 turbines. ↓ Array of 50 RM1 turbines ↓ Tool optimised arrays produced 	Integrated & Standalone
Energy Transformation	<ul style="list-style-type: none"> Simplified M100-D electrical design ↓ More complex M100-D electrical design tested RM1 electrical design ↓ 	Integrated
Energy Delivery	<ul style="list-style-type: none"> Direct cable connections ↓ Other electrical architectures tested 	Integrated & Standalone
Station Keeping	<ul style="list-style-type: none"> Gravity foundation ↓ 	Integrated

¹⁰ Version 1.1.3 (20 Sept. 2021)

Module	Summary of cases tested & data flow	Mode assessed
Logistics & Marine Operations	<ul style="list-style-type: none"> • Default assumptions and catalogues (integrated) ↓ • Refined assumptions and catalogues to better represent EnFAIT array (standalone) 	Integrated & Standalone
System Performance & Energy Yield	<ul style="list-style-type: none"> • Inputs from previous modules 	Integrated
System Lifetime Costs	<ul style="list-style-type: none"> • Inputs from previous modules and representative parameters of an ocean energy project 	Integrated
System RAMS	<ul style="list-style-type: none"> • Inputs from previous modules (tested but did not work) 	Integrated
Environmental & Social Acceptance	<ul style="list-style-type: none"> • Simplified case using inputs from previous modules • More detailed case tested at highest complexity, but did not work 	Integrated
<i>Stage Gate</i>	<i>Not used/tested in EnFAIT</i>	—
<i>Structured Innovation</i>	<i>Not used/tested in EnFAIT</i>	—

The DTOceanPlus tools offer increasing levels of complexity, as noted in section 2.2. For the comparison with the EnFAIT array, the highest level of complexity has generally been used, as this offers the greatest detail and fidelity. The lower levels of complexity are aimed more towards early-stage technology and project development, so are not as relevant for EnFAIT. Lower complexity was used where detailed data was not available, or where errors occurred in the higher complexity mode.

The following section covers general comments and feedback relating to the overall suite of tools, with overall limitations and potential future improvements identified. This is followed by discussion on the installation of the DTOceanPlus tools.

Section 5 then covers the assessment of each module/tool within the DTOceanPlus suite in turn, by:

1. Summarising the tool and its use cases, building on the tools' documentation [10].
2. Comparing the modelling fidelity and results with EnFAIT array (where applicable).
3. Discussing any limitations and future improvements identified, which will facilitate future development and enhancement of the tools.

As part of the EnFAIT project, the documentation for the tools has been reviewed. This includes a review by a user not familiar with the DTOceanPlus tools, which has helped to identify any areas that were less clear or missing details. Work is ongoing as part of the EnFAIT project to update the overall DTOceanPlus documentation, to address the shortcomings identified and add additional detail where possible.

Additional evaluation, results, and lessons learnt from using the Energy Capture, Energy Delivery, and Logistics & Marine Operations tools in standalone mode to model potential future arrays will be reported in EnFAIT D10.6.

4.2 Overall limitations and future improvements to the DTOceanPlus tools

With all tools, there are always minor limitations and further areas that could be improved in future. This section collates those that are applicable to the overall suite of tools and/or several modules. Further improvements are discussed in the relevant modules' section where appropriate.

Although it has been possible to successfully test a huge amount of the functionality of the DTOceanPlus tools, throughout this testing various errors have occurred, which is perhaps to be expected with new software. Importantly, the underlying cause is not always clear. Some errors appear to be a result of input data being incorrectly formatted or missing required information; this could be alleviated by improved documentation. Other errors appear to be caused by an underlying bug or error in the code. The error messages to the user are also sometimes unclear, and in some instances not presented to the

user in the GUI. These software errors should be resolved, along with further checking of input data and improved error messages for the user.

In terms of the overall data flow and storage of using the tools:

- In integrated mode, the modules must all be used sequentially, it is not currently possible to skip one or more modules in the design chain and have the user input the required information. In theory, it is possible to run a set of modules all standalone and this could skip a module. In practice, however, formatting the data correctly will likely make this unworkable.
- Data for a project is stored separately within each module. This is not a significant limitation in itself, but it compounds the next point.
- There is currently no way to save/export or load/import a project or study. Within the DTOceanPlus project, a standard data format for ocean energy systems was developed, called a “Digital Representation” (DR), see [20] for details. The functionality exists to export a DR of a study; however this was not fully working when tested in this assessment. It is also not currently possible to import a DR.

In terms of running the calculations:

- It appears that there is no way to abort the calculation process once this has started. This is especially an issue for modules with longer computation. This is compounded by the fact it is not always clear what stage the calculation has progressed to.
- Debugging errors and viewing detailed calculation progress is not always straightforward. There are also different ways of doing this between the modules. Some of the error messages can be cryptic, often originating from the underlying Python code. These error messages generally do not fully explain what has gone wrong and/or how it might be resolved. A required future improvement to the tools is therefore to improve the overall presentation and clarity of error messages. This can and should be complemented by more detailed documentation on how to resolve common errors.
- Differing conventions are used between modules. There is not a standardised approach to the process of using each module. How inputs from previous modules are handled in integrated/standalone modes can be different. Although a minor point, the GUI is different between modules in terms of navigating the inputs, calculations, and results. This is also true of how the modules can be used in standalone mode, with some modules allowing access to a list of studies via the left menu, even in integrated mode. Similarly, the level of detail recorded in the application logs, and where these are accessed varies.

Finally, some possible improvements to the user interface and documentation:

- A useful future improvement for all modules would be an easy way to export results in a tabular format. This would facilitate further analysis in a spreadsheet or some other software. Some modules make the results available in JSON format¹¹, and all results are available in JSON format via the API, however, this is not so convenient for spreadsheets which are more universally used with a lower barrier to entry.
- Another useful addition throughout the tools would be the ability to overlay plots of different spatial information, such as bathymetry and current speed. It would also be beneficial to be able to view this information in more places, for example to visualise the bathymetry within Energy Capture or Energy Delivery. Related to this is the display of UTM coordinates on plots, which are sometimes shown in scientific notation making them more difficult to interpret.
- Numerical values are often quoted with over precision, typically the 15-17 significant figures available in Python double-precision numbers. When hundreds or thousands of values are saved like

¹¹ JavaScript Object Notation, a lightweight data-interchange format that is easy for humans and machines to read and write. <https://www.json.org/json-en.html>

this in csv/JSON format, it can significantly increase the file size of outputs and data transfers between modules. This precision is not warranted, for example device coordinates from Energy Delivery can be output to the nearest nanometre, when in reality the nearest meter is appropriate given the other uncertainties in the design.

- For some modules, it is difficult to check the complexity level of an existing study, as this is not always displayed in the GUI. This should clearly be reported in the main module as well as the GUI of each module for the case of using standalone. As a workaround, the user can add this information in the description of the study.
- More guidance/help on appropriate ranges/values of input parameters that might typically be used would always add value and make it easier for the user. Because DTOceanPlus covers such a wide range of design and assessment areas, it is likely the user will not be an expert in all. However, it is noted the nascent status of ocean energy means there may not be established standards or guidance available.
- Some sections of the documentation are incomplete or marked as draft. The documentation has been reviewed as part of the EnFAIT project assessment, and any missing or incomplete areas will be highlighted to facilitate future development.

4.3 Installation of DTOceanPlus

The installation of DTOceanPlus is a two-stage process. Firstly, installing and running Docker Desktop, which is the software environment in which the tools are run. Secondly, an installer script/application is downloaded from the project GitLab repository¹² and saved in a folder on the user's computer where DTOceanPlus is then installed, referred to as the installation folder. On running this installer, the user can choose which of the module(s) to install. The relevant code is then downloaded, and the modules deployed. Once installed, the DTOceanPlus module(s) run in the background whenever Docker Desktop is running, and they are accessed via a web browser interface.

4.3.1 Docker

As noted in section 2.2, the DTOceanPlus tools run within Docker containers. From the Docker Documentation [21] *"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. ... Containers isolate software from its environment and ensure that it works uniformly despite differences for instance between development and staging."* This allows the DTOceanPlus tools to be installed on Microsoft Windows, Apple macOS, and Linux computers.

As of 31 August 2021 Docker Desktop is no longer free for all users. It is noted that *"Docker Desktop can be used for free as part of a Docker Personal subscription for: small companies (fewer than 250 employees AND less than \$10 million in annual revenue), personal use, education, and non-commercial open-source projects"* [22].

DTOceanPlus requires the legacy 'Hyper-V' backend within Docker. It does not currently run using the WSL2 based engine, although according to Docker this could provide better performance.

The DTOceanPlus documentation recommends at least 8GB of memory (RAM) to be allocated within Docker. However, memory issues were encountered when testing LMO with all modules installed and running in Docker, as detailed in section 5.9. Increasing the memory limit to 12GB resolved these issues. DTOceanPlus therefore requires a moderately powerful computer to run, with 16GB or more memory.

¹² https://gitlab.com/dtoceanplus/dtop_inst/-/packages

4.3.2 Limitations and future improvements

Installation of the DTOceanPlus tools requires administrator privileges on the computer to run the installation scripts. These scripts are currently unsigned, and so may be prevented from running by security software or company policies. The folder in which DTOceanPlus is installed cannot contain any spaces in the full path to that location, which might cause an issue for some users. It is understood this is just a limitation of the installation script.

Two methods are available to install DTOceanPlus on Windows, the Windows installer application and a cross-platform installation script. These are downloadable from the GitLab package repository as 'dtop_win_inst' and 'dtop_inst_windows' respectively. This offers scope for confusion. Given the cross-platform installation script is not very user-friendly, it could be removed as an option for Windows installation. The DTOceanPlus Windows installer provides all the basic functionality required to install the tools, but it not particularly polished.

The default databases for the Site Characterisation need to be downloaded separately and the '.tar.gz' archive copied to the installation folder. If this archive is not copied to the correct folder, the installation script skips this step. It does not provide any warning, although it is recorded in the installation log. It would be more user friendly if downloading and installing the SC databases was part of the installer script in the same way as the required modules' code is downloaded from GitLab.

5 Assessment of individual DTOceanPlus modules

This section covers the testing each module/tool within the DTOceanPlus suite in turn, by:

1. Summarising the tool and its use cases, building on the tools' documentation [10].
2. Comparing the modelling fidelity and results with EnFAIT array (where applicable).
3. Discussing any limitations and future improvements identified, which will facilitate future development and enhancement of the tools.

5.1 Main Module

5.1.1 Summary of tool and use cases

The Main Module (MM) is used to manage projects and studies. It provides the starting point for use of the other modules, managing integrated and standalone used of these modules. It provides a clear and simple interface to do this.

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.

The main module is set up to manage multiple users, to facilitate use within a company intranet, or future development as a cloud-based software-as-a-service. Each user has their own workspace, but projects can be shared with other users to facilitate collaboration. When using DTOceanPlus individually on a local computer, this does however add an additional layer of friction, as it requires login every time.

5.1.2 Limitations and future improvements

Once a machine or site is selected it is not possible to change it within a project. Additional projects are required to consider different sites or machines. This is not a significant limitation, but the user needs to be aware of this approach.

When forking a study, the user must manually go back to the list of studies and then open the newly forked study to continue. The GUI could also be made clearer that the module selected is the one to fork after, and not the one in which the alternative design can be considered. I.e., to consider a different foundation solution, the user must fork after Energy Delivery. This is explained in the documentation.

The naming of entities (the unique use of a module within a study or project) is slightly unclear, by default these include the project and module but not the study. For some modules, a description or tags are mandatory inputs when creating a new study, which seems an unnecessary requirement.

5.2 Catalogues

5.2.1 Summary of tool and use cases

DTOceanPlus contains a series of catalogues of components and reference data used in the design modules as summarised in Table 5.1. These come pre-populated with example data not linked to any specific manufacturer, and three of these catalogues have been released as open-source datasets for use in other contexts [23]–[25]. There is a dedicated catalogue module to browse and manage the catalogues and data, although the data can also be requested by individual modules via the API.

Table 5.1. DTOceanPlus catalogues of component/reference data

Catalogues Group/Module Using	Catalogue Tables
Power Take Off Components Energy Transformation	Air turbines; Gearboxes; Hydraulic transmission systems; Generators; Power converters; Control systems
Electrical Network Equipment † Energy Delivery	Static cables; Dynamic (umbilical) cables; Wet-mate connectors; Dry-mate connectors; Collection Points; Transformers
Mooring Line and Anchors † Station Keeping	Mooring line properties; Drag anchor dimensions
Logistical Infrastructure and Equipment † Logistics and Marine Operations	Activities; Speeds for different operations; Installation operations; Maintenance operations; Decommissioning operations; ROVs; Divers; Cable burial equipment; Cable protection equipment; Pilling equipment; Terminals at ports; Vessel operations; Vessels
Cost Benchmarks System Lifetime Costs	Benchmarks

† Data also published as open-source dataset on Zenodo [23]–[25].

While some of the values, particularly cost, were not in line with experience within the EnFAIT project, it is possible to update these values within the Catalogue module. Further comparison with the EnFAIT array is discussed per module in the subsequent sections.

Although some errors were encountered with the Catalogues module, the interface provides an intuitive and useful way to manage the reference data and components used by the design modules.

5.2.2 Limitations and future improvements

A few errors were encountered when trying to use the logistical infrastructure and equipment catalogues. It was not possible to debug the cause of these, but they need to be fixed to fully use the LMO module in integrated mode. The data for the vessels catalogue is not displayed in the GUI, and the API returns a code 500 ‘server error’, but it is not known what is causing this. It is not currently possible to add or edit a terminal where any value is noted in the slipway field, as shown in Figure 5.1a. The general notes field for Terminals only accepts numeric values as shown in Figure 5.1b. An incorrect data-type setting may be the cause of these errors, so it could be a simple fix.



Figure 5.1. Error messages displayed in the Catalogue module when trying to edit a Terminal. (a, left) when there is a value in the slip (slipway) field, and (b, right) when there is text in the general notes field.

While a filter operation is provided for each column, this has very basic functionality. It is a free text input, but this only matches the exact (case-sensitive) value of a field, there is no partial matching or numerical filtering included at this point. For example, in the port terminals catalogue, filtering “UK” in the country field does not match entries for “The UK”. Similarly, trying to filter for Draught “>10” results in no data displayed and the catalogue page then needs to be reloaded to view entries. The filter on the catalogues home page does however progressively refine the list with only entries partially matching the text entered.

5.3 Site Characterisation

5.3.1 Summary of tool and use cases

The Site Characterisation (SC) module is used to characterise the site, including metocean, geotechnical, and environmental conditions. It includes time series of pertinent parameters and calculates statistics on these parameters including probability distributions, scatter diagrams, and extreme values. The environmental conditions are then used as inputs to the design tools. As well as seabed bathymetry it considers superficial deposit material, e.g. rock, sands, clays, and the presence of marine species. In terms of metocean environmental conditions, waves, tidal currents, winds, and water levels are included.

For tidal sites, the SC module summarises the tidal timeseries into a probability distribution of flows. For the higher complexity (levels 2 & 3) the most representative timestep is selected to maintain the spatial variability of flow. This follows a similar approach used in the data pre-processing for the DTOcean hydrodynamic module [26].

Low and medium complexity

For complexity levels 1 and 2, sample data is provided for nine sites with varying levels of wave and tidal energy (low, medium, or high); details are given in Table 5.2. The reference sites are all located along the French coast with comparatively large lease areas. For complexity 1, timeseries data is only provided at the lease centre point, whereas at level 2, spatially varying data is provided across the site.

Having these example sites could be helpful for many users, as site data is often difficult to obtain.

Table 5.2. 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 Brieuc	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

High complexity

At complexity 3, the user can upload their own data, which is processed by the SC module. This comprises the geometry of the lease area and export cable corridor (as GIS shapefiles), details of the seabed type, roughness, species, and bathymetry (all as NetCDF files¹³), and timeseries of environmental conditions (in csv or NetCDF format). The 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. They can optionally also be provided in 2D, varying both temporally and spatially¹⁴.

¹³ 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/>

¹⁴ Note that the spatial dimension is normally 2D, but this is stored as a single dimension of node position in the NetCDF file.

Example geometries and timeseries are provided for a couple of sites. There are also default databases for the other parameters, see [27] for details. Unfortunately, these are very low resolution, at $0^{\circ}00.25'$ ($\sim 450\text{m}$) for French coastal waters and $0^{\circ}05'$ ($\sim 9\text{km}$) 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.

5.3.2 Comparison with EnFAIT array

Given the reference sites are all located in French waters, these do not represent the EnFAIT array well. The logistical operations become less meaningful if they are located in another country, however this might still provide a rough indication of the types of operations required at an earlier stage of technology development where the deployment site(s) are not known.

At the highest complexity, it is possible to enter data to model the Bluemull Sound site. However, the Site Characterisation module cannot accurately represent the EnFAIT site, due to several limitations in the current implementation.

The processing in SC includes a padding around the lease area to allow any data points just outside the lease boundary to be included in the calculations. However, this is always a set value of 0.01° ($\sim 1.1\text{km}$ latitude), which is excessive for small sites. The EnFAIT site is approx. $300\text{m} \times 300\text{m}$, while the resulting padded output from SC is approx. $1350\text{m} \times 2250\text{m}$, as shown in Figure 5.2. This also applies to the export cable corridor.

Another key limitation shown in Figure 5.2 is that the bathymetry is always returned as a 10×10 grid of points for the site lease area and export cable corridor. These are given in WGS84 degrees, whereas Energy Capture, Energy Delivery and Station Keeping use data in UTM meters for calculations, and therefore must convert and interpolate the bathymetry data. For the EnFAIT array, the bathymetry would ideally have a grid spacing of around 25m , however this may vary for larger sites.



Figure 5.2. Input lease area and export corridor and output bathymetry points from Site Characterisation module

The summary of the currents provided in the SC results page closely matches a standalone assessment of the full resolution data, as shown by the similarity in Figure 5.3 (a) and (b). However, when this is summarised into a series of environmental conditions and passed to the other modules it loses fidelity, as shown in Figure 5.3 (c).

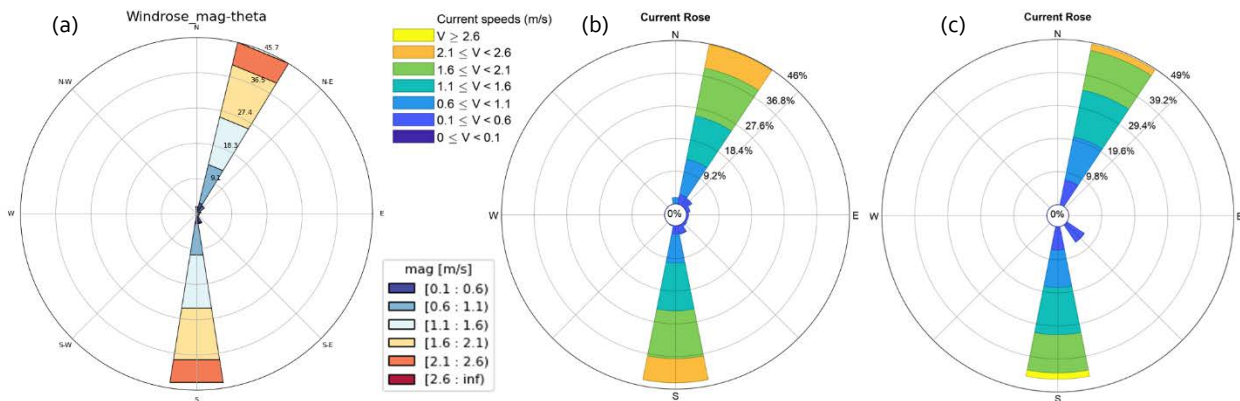


Figure 5.3. Comparison of tidal resource for 1D (temporal) assessment, (a) output from DTOceanPlus Site Characterisation module results page, (b) direct analysis of tidal resource model at array location, and (c) analysis of summarised output from Site Characterisation used in the Energy Capture calculation. Note colours differ between plots, but velocity bins are the same.

This is because the environmental conditions, i.e. tidal resource, is not sufficiently granular to model a tidal array accurately. The SC module always generates between 2-15 probability bins of tidal velocity, depending on the range of values for that site (note this covers the full variation between flood and ebb tides). For the Bluemull site data, this results in 11 bins of 0.5m/s. For the 2D analysis case (varying both spatially and temporally), these probability bins appear only to be defined in the calculation code by the east-west u velocity component with the north-south v component neglected. This a significant limitation at Bluemull, where the channel alignment is predominantly north south.

The occurrence probability of the flow conditions is based on a single point of interest, although these maintain spatial variability as discussed above. In DTOceanPlus this point is taken as the geometric centre of the lease area, which is a slight regression from DTOcean where this was a user input coordinate, and so could therefore be set close to the device locations.

5.3.3 Limitations and future improvements

The major limitation of the Site Characterisation module in its current state is how it deals with the spatial extents of the site. The site and lease bathymetry are always provided as a 10×10 grid of points, which is not of sufficient detail to model a tidal site. This also has a fixed amount of padding applied, which is excessive for small sites. Finally, the bathymetry is output to WGS84 coordinates, but EC, ED & SK all then separately convert to UTM for calculations. The first two of these should be relatively straightforward to implement, increasing the number of bathymetry points and setting the padding to a fraction of the site size. As SC is the first module in the design chain, and its output used in most modules, this would also require extensive testing to ensure this did not inadvertently break other functionalities.

The site bathymetry output from SC could be given in UTM coordinates, ideally with a user option to specify the resolution in metres, noting that higher resolution will increase computation time in later modules. This would require updates to the API and EC, ED & SK modules that use this data, along with extensive testing. The user may already have the site bathymetry in UTM coordinates, so it would be a useful option to upload the data in this format to avoid the need for conversion.

For defining the environmental conditions, the total velocity vector must be considered, not just one component. Flood and ebb tides should both be considered, with the latter as negative velocities; this would require identifying the principal direction of each. Alternatively, it may be possible to bin u, v components together as a complex number representing the vector. The number of probability bins should be increased, ideally to a 0.1m/s resolution as suggested in IEC-TS-62600-200 Electricity producing tidal energy converters — Power performance assessment. This is extremely important for calculating the AEP and thus revenue correctly, impacting on LCOE and project IRR.

Being able to separately define the wave and tidal resource would be useful and add flexibility. Either with differing timesteps as highlighted in [14], or making use of the example wave data but uploading a tidal time series (or visa-versa). It may also be possible to make use of environmental data recently released from the RESOURCECODE project¹⁵.

Similarly, there should be the option to allow the user to specify the point of interest to calculate the environmental condition probability, as was the case in DTOcean. This could default to the lease area centre if not specified.

The output from SC may sometimes contain NaN (Not a Number) values, which could result in uncertain behaviour of other modules, although it is not known to have caused any errors. The value 'NaN' is not strictly valid JSON format; it must be replaced with 'null' to format the JSON in some tools¹⁶.

As noted earlier, it would be useful to be able to overlay different graphical outputs, such as bathymetry and currents, on the same plot. Having each separate is useful for clarity but overlaying two layers could facilitate comparison and understanding of interrelationship.

The module assumes 2D inputs are unstructured data, to be re-gridded which takes a significant amount of the processing time. It could be a useful addition to be able to upload gridded data from some other pre-processing tool to use in DTOceanPlus.

There are a couple of points where additional documentation would be very useful:

- More guidance should be given on the details of the nine reference sites, e.g. what the maximum waves and currents are. Table 5.2, or similar, could be added to the documentation to address this.
- The required structure for the NetCDF input data files is not clearly documented. It appears that the coordinate system is always assumed to be WGS84, but this is not explicitly defined in the example files, therefore it is not possible to import these into QGIS to view them.

Overall, it would be useful to give the user more control over the inputs and outputs from SC, as at present it is limited in what the user can achieve using these tools integrated.

5.4 Machine Characterisation

5.4.1 Summary of tool and use cases

The Machine Characterisation (MC) module is primarily an input module to define device prime mover. These are grouped into three categories, which for tidal devices at complexity 3 are:

1. *General inputs*: cost, fixed/floating, foundation type, electrical connector type (wet-/dry-mate), rated capacity, min/max installation water depth, and material quantities .
2. *Dimensions*: rotor diameter, hub height, total height/width/length, draft, total mass, submerged volume, wet area simplified profile (cylindrical/rectangular), wet area, wet frontal area, dry area simplified profile, dry frontal area, and footprint radius.

¹⁵ <https://resourcecode.ifremer.fr/>

¹⁶ e.g. JSON formatter plugin for Chrome, or JSON Viewer plugin for Notepad++

3. *Model*: whether a bi-directional turbine, number of rotors and rotor inter-distance, heading angle span, power/thrust coefficients at a range of velocities, and cut-in/-out velocities.

These parameters are then used in the other deployment design tools. The parameters vary between wave and tidal devices, and the model also differs by complexity. For wave energy devices at high complexity, the MC module also estimates coefficients used in the energy capture analysis. The complexity level chosen for MC sets the complexity level for Energy Capture, since this depends on the hydrodynamic model in MC.

Additionally, the MC module contains a default set of machines: the 1.1MW RM1 twin-rotor tidal turbine and 0.3MW RM3 point absorber WEC from the US DoE Reference Model Project [19], plus generic heaving buoy and surging barge WECs. The parameters of these can then be adjusted within MC, before locking the machine to conduct the analysis.

5.4.2 Comparison with EnFAIT array

It is not currently possible to specify the geometry of a gravity base foundation sub-structure separately to the main device in MC, and it is unclear how such a sub-structure should be modelled within DTOceanPlus. This is also discussed with reference to Station Keeping and Logistics and Marine Operations in sections 5.8 and 5.9. For the Nova turbines, see section 3.1.2, the gravity base is deployed to the seabed and then the turbine nacelle lowered in a separate operation.

No further comparison with the EnFAIT array was performed for MC as this is not applicable.

5.4.3 Limitations and future improvements

It is not always apparent what the various parameters refer to in the MC inputs. For example, it is not clear that hub height actually refers to depth below surface for floating devices. Similarly, what does draft represent for fixed devices transported on deck? An annotated diagram would make this clearer. It is also not always apparent how these parameters are used in further calculations, as noted in [14].

While it is possible to download the details a completed machine and to upload a previously defined machine, this functionality does not currently work properly. Trying to re-upload the downloaded entity, results in an error: “Wrong file format. The JSON file must contain the following keys: project, general, dimensions, model, hydro”. It seems the project information is not exported, but it is required for the import. It also does not appear possible to upload and use a machine within a project, it must first be uploaded within another project then selected in main module interface of a second project.

When reviewing the list of machine characterisation entities, clicking the ‘remove’ link immediately and permanently deletes that machine entity with no warning. If this machine entity is being used in a project, that project becomes corrupted and cannot be used further.

Once the machine object is locked it is not possible to unlock it, even if there are no studies that reference it. While this is understandable for data consistency reasons, it could be useful to provide the opportunity (with sufficient warning) to users, so that they don’t have to start a completely new project just to correct a typo made at the start of the project. This also impacts on the ability to assess some parameters in later modules, as these are set and locked in MC. For example, connector type in Energy Delivery, or foundation type in Station Keeping. It may be more appropriate to have these inputs in the relevant later module.

5.5 Energy Capture

5.5.1 Summary of tool and use cases

The Energy Capture (EC) tool is used to calculate the hydrodynamic energy captured by devices and the array interactions between them. It can either be used to assess a user input array or suggest an optimised array layout from a hydrodynamic perspective. In this latter case, the best layout is defined based on the maximisation of the annual energy production, with the given constraints in the minimum q-factor and the minimum distance between devices.

After selecting/defining a site and machine, EC is run first in the chain of DTOceanPlus design tools.

Further testing and analysis of potential future layouts for larger arrays will be completed within the EnFAIT project using the Energy Capture tool in standalone mode, to be reported in D10.6.

5.5.2 Comparison with EnFAIT array

The accuracy of Energy Capture in integrated mode is impacted by the limitations in the environmental data from the Site Characterisation module, discussed in section 5.3. As the 1D analysis (i.e. not spatially varying) in SC gives a reasonable approximation of the flow conditions, the results from EC using this are similarly accurate. However, this does not capture the variation in energy resource across the site.

It is possible to use EC in standalone mode and provide much more detailed input data to model the spatial variation of flows across the site with a greater number of velocity bins.

Within EC, all devices in an array are considered to be of the same type, therefore it is not directly possible to model the full EnFAIT array with three M100 and three M100-D turbines. Since the wakes of the different models will be similar, within the limits of the EC model, it would be possible to calculate the performance of arrays comprising only each turbine model, then aggregate the results to match the EnFAIT array configuration.

When using the optimisation algorithm, the maximum number of turbines appears to be limited to 24, with streamwise and transverse spacings of 7.5 turbine diameters. While there are no standard array layouts, this spacing is higher than mentioned in the literature.

5.5.3 Limitations and future improvements

For some sites in integrated mode, the output from SC did not meet the requirements for EC, and thus EC was failing with a 'Lease Area vertex' error. The 2D matrix of currents from SC did not cover the same extent as the full padded site boundary, and thus it was not possible to run EC for these cases. This is a limitation of SC and integration between modules.

The depth averaged velocity vector given on the site inputs page, and the arrows representing the resource on the array layout plot, both appear to consider the mean velocity. The mean wave direction may be a meaningful result to plot, but the mean of the ebb and flood tides less so. It would be more useful to show the mean of the ebb and flood tides separately, or just the direction of the strongest tide if only one arrow can be plotted.

The results from Energy Capture do not include the device angle, although this is an input to the user specified layout. It is therefore not apparent whether the optimization algorithm includes device angle for non-yawing devices. The vertical location of the device is also not presented in the results, although this is only relevant for seabed fixed devices.

A nice-to-have enhancement would be able to click the map to place/relocate devices, rather than having to manually enter the coordinates.

When using the layout optimisation, the ‘4-parameter’ array type does not appear to work with the default optimisation method, this gives the error “RuntimeError('Invalid results retrieved from the Worker. ')” . Regarding the default optimisation method, it is not clear if this is the ‘brute force’ method described in the alpha-version [28], and so this should be clarified.

A minor point with the display of the Q-factor results plot, is the results only show 1 decimal place, therefore it gives a result of 1.0 when the true value is actually 0.964, see Figure 5.4. The full results can only be found within the API.

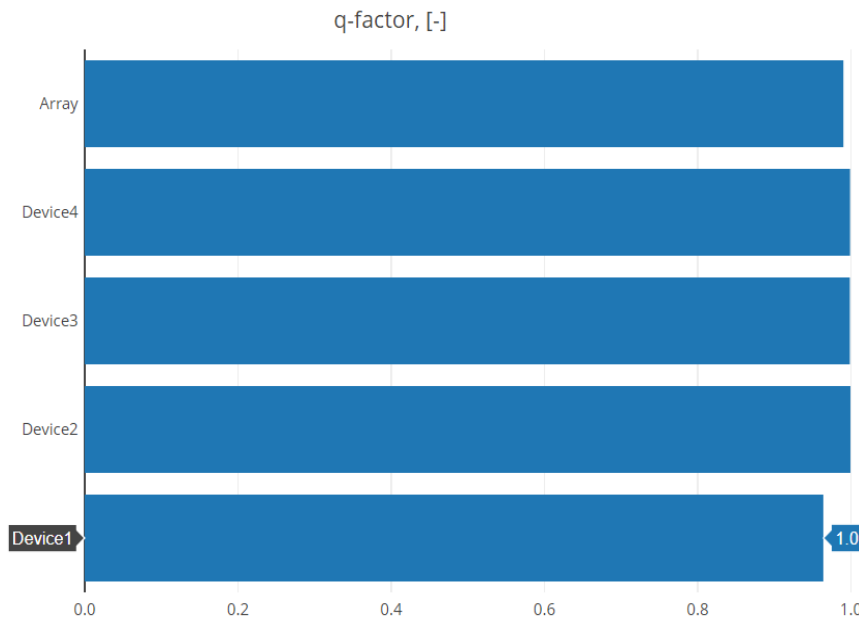


Figure 5.4. Q-factor results plot in EC does not show sufficient precision in the results.

5.6 Energy Transformation

5.6.1 Summary of tool and use cases

The Energy Transformation (ET) tool is used to design PTO and control solutions. It calculates efficiency and energy losses in three steps: mechanical transformation, electrical transformation, and grid conditioning. Unlike other modules which have a single level of complexity, each step can be run at each complexity level, although complexities 1 and 3 are not considered compatible given the differing levels of detail/precision.

Table 5.3. Energy Transformation module options at complexity 2/3

Calculation step	Tidal Turbines	Wave Energy Convertors
General inputs	<ul style="list-style-type: none"> Device Shutdown flag (Minimum number of PTOs required to be operational) 	<ul style="list-style-type: none"> Device Shutdown flag Number of parallel PTOs
Mechanical transformation	<ul style="list-style-type: none"> Gearbox Direct drive 	<ul style="list-style-type: none"> Linear to rotational Hydraulic Air turbine (wells/impulse)
Electrical transformation	<ul style="list-style-type: none"> Squirrel-Cage Induction Generator (SCIG) Permanent Magnet Synchronous Generator (PMSG) 	
Grid conditioning	<ul style="list-style-type: none"> One option with multiple input parameters 	
Control	<ul style="list-style-type: none"> Passive 	<ul style="list-style-type: none"> Passive User defined

5.6.2 Comparison with EnFAIT array

It is possible to model devices with either a gearbox, or a direct-drive generator in ET. To assess a direct-drive generator, mechanical complexity level 2 or 3 must be selected; a simplified representation of the mechanical losses is considered at complexity level 1.

As noted during the DTOceanPlus tool demonstration [14], the ET module perhaps requires an unnecessary level of input data, which could more simply be represented by a load-efficiency curve from the manufacturer. The module is calculating losses from several sources: mechanical losses, iron losses, winding losses, capacity losses, plus brush and rotor losses for SCIG or magnet losses for PMSG. This level of analysis does not necessarily add much value within the EnFAIT project, but maybe useful for early-stage WEC concepts.

During the testing of ET, the results initially showed power capture significantly higher than rated power and with very high failure rates. This problem appears to be resolved with an update made to the code in June 2022. This test was a direct drive turbine and complexity level 1 for electrical transformation and grid conditioning steps. The resulting failure rates were approximately 3.5 failures/year for each generator. This caused issues when testing LMO as discussed further in section 5.9. It is not clear from the ET module inputs or outputs what was causing these high failure rates, but it is very likely a result of the generator being used at over 250% of rated power from the power capture error. Nova’s experience with the EnFAIT array is that the generators have been extremely reliable, with no failures experienced.

For some environmental conditions, ET is showing slightly more power captured by the device than the EC module, see Table 5.4. Note that the mechanical stage is the same as captured as it is a direct-drive turbine, there are no gearbox losses in this case. There were however very high losses at the electrical transformation stage in this example, although it was unclear why, but it might be the input assumptions were suboptimal. The Nova turbines generally capture slightly more than 100kW at the rotor shaft and produce 100kW at grid.

Table 5.4. Power at a range of environmental conditions for a 100kW rated direct-drive tidal turbine at different steps in the calculation, showing slightly increased captured energy in ET than in EC and very high losses at the electrical stage.

Environmental condition ID	Energy Capture (kW)	Energy Transformation (kW)			
		Captured	Mechanical	Electrical	Grid
0	100.00	100.90	100.90	25.64	25.08
1	100.00	100.90	100.90	22.18	21.67
2	83.25	84.00	84.00	16.13	15.72
3	26.35	26.58	26.58	4.40	4.24
4	26.60	26.81	26.81	4.44	4.27
5	97.12	97.92	97.92	19.18	18.72
6	100.00	100.90	100.9	22.64	22.12
7	100.00	100.90	100.9	25.39	24.83

5.6.3 Limitations and future improvements

There does not appear to be a way to see the progress of the calculation, which can take some time, depending on the inputs. There also does not appear to be a way to view the backend calculation logs to help understand the calculation process and any errors that may occur.

As noted in the module documentation, the tool can be very sensitive to the user inputs/design choices, however little guidance is given on this. This can lead to high losses, with low or no power output in many/all environmental conditions.

While the module calculates losses at different steps, these losses are not presented as such, only the absolute value for power and energy is reported for each step. Adding the percentage losses at each stage would aid understanding of the results.

The presentation of the results could be improved with graphical representation of key parameters. Where tabular data is presented, it could be nice to show parameters in columns, with a row for each device and a total for the array, rather than split into multiple locations, as shown in Figure 5.5. Similarly, multiple PTOs per device could be added as additional rows under the device.

Assessment - Energy			Assessment Energy (kWh) ⓘ	Mechanical Energy (kWh) ⓘ	Electrical Energy (kWh) ⓘ	Grid Conditioned Energy (kWh) ⓘ
Quantity	Unit	Value				
Annual Captured Energy ⓘ	kWh	886637.42	842,605	842,605	176,418	172,554
Annual Mechanical Energy ⓘ	kWh	886637.42	842,605	842,605	176,418	172,554
Annual Electrical Energy ⓘ	kWh	191237.24	842,605	842,605	176,418	172,554
Annual Grid Energy ⓘ	kWh	187103.92	421,303	421,303	88,209	86,277
			421,303	421,303	88,209	86,277
			3,370,420	3,370,420	705,672	690,216

Figure 5.5. (left) Example output from ET with separate sections for each PTO, device, and array total, (right) Mock-up of a tabular-style output

It should be made clearer where default values are given in the GUI inputs page that need updating by the user. Related to this, the rated power input for each step should be set to the rated power of the machine divided by number of PTOs, rather than the somewhat arbitrary 500kW default used. More guidance on what ranges of values should be considered would also be helpful.

The Energy Transformation module does not include the option for voltage transformation onboard the device, it always assumes a 690V generator. This may also contribute to the high generator losses. The transformer issue is linked with Energy Delivery, as discussed below.

It may also be beneficial to add an allowance for ancillary power requirements of the device within ET.

5.7 Energy Delivery

5.7.1 Summary of tool and use cases

The Energy Delivery (ED) tool designs an electrical network to transmit power from devices to shore. This includes 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)

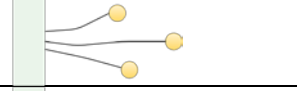
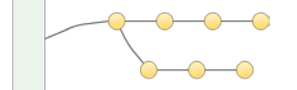
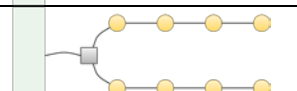
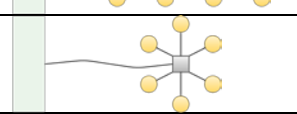
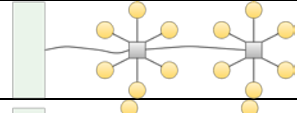

The design is based on user choices, design parameters from other tools, and a catalogue of typical electrical components.

Six different network topologies are considered within ED, shown in Table 5.5 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 of 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 5.5. Details of electrical network topologies in Energy Delivery [1].

Network topology	Array CP	Transmission CP	Simplified diagram
Direct to shore	No	No	
Radial	No	No	
Radial with transmission collection point	No	Yes	
Single cluster star	No	Yes	
Multi-cluster star	Yes	Yes	
Multi-cluster star with transmission CP	Yes	Yes	

At complexity 1, a simplified design algorithm with radial arrays around a collection point is always assumed, although direct connection is used for single devices. This simplified design considers only device spacing and distance to shore to calculate cable lengths. Umbilical cables are not directly considered for floating devices.

Further testing and analysis of potential future electrical networks for larger arrays will be completed within the EnFAIT project using the Energy Delivery tool, to be reported in D10.6.

5.7.2 Comparison with EnFAIT array

With the release of DTOceanPlus, it is now possible to model the individual connections to shore used in the existing EnFAIT array, as well as the subsea hub proposed for the additional turbines. This was not possible in DTOcean v1.0/2.0, which always assumed a surface piercing substation. However complexity level 2/3 is required to model the direct connections to shore per turbine. Seabed lay of cables, as used in EnFAIT, is now an explicit option in DTOceanPlus, compared with having to set the burial depth to zero in DTOcean.

It is not possible to model the full EnFAIT array with some turbines connected directly to shore, and others connected via a subsea hub. The ED tool only considers one electrical architecture per array, which is the expected case for future commercial arrays.

The electrical costs are higher than Nova's experience, although these can be updated within the catalogue as required. It is also highlighted that connector costs do not vary with voltage in the default

catalogue, due to limited data availability. Nova’s experience is that there are significant step-changes in cost for increasing voltages of connectors.

The default installation cost proxies provided in Energy Delivery are also much higher than considered for EnFAIT, but these can easily be changed in the GUI. The cost proxies are only used for the selection of the best design, the installation costs are not included within the Energy Delivery results. Installation costs must be added for a fair external comparison of networks.

The energy delivery tool does not consider spacing between parallel cables, nor penalise cable crossings. Instead, it allows multiple cables to follow the same route, as shown in Figure 5.6. This might give a slight underestimate in terms of overall cable length. With many cables, the space required for the cable corridor could be more significantly underestimated, as it may not be feasible to install multiple cables in close proximity to each other.

In some instances, the cable routes calculated in Energy Delivery go between and/or close to other devices, which could be difficult to install, as also shown in Figure 5.6. It should be noted however, the algorithm used to determine the cable route is not intended to produce a detailed design but estimate cable lengths, costs, and losses.

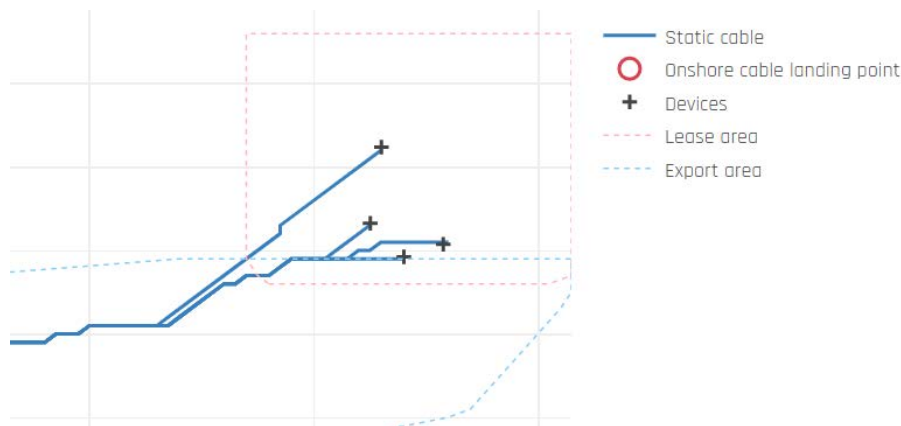


Figure 5.6. Screenshot of Energy Delivery network schematic, showing overlapping cables and a cable routed between devices

5.7.3 Limitations and future improvements

As mentioned above, the tool does not represent spacing between parallel cables. It also does not penalise cable crossings which are typically avoided where possible. Within the GUI, it can appear that multiple cables are only one, which has been clarified in the documentation.

The input data format should be checked earlier in the calculation process, or ideally on the inputs page. For example, if the landing point coordinates are not within the export corridor, the user is not quickly alerted to this error.

To speed up multiple calculations considering different options at the same site, it might be possible to cache the network graph representing a particular site, as this seems to take a significant chunk of the analysis time to produce.

It would be useful to (optionally) manually specify the location of the collection point, as in some instances the CP location can appear suboptimal. This was highlighted from the testing of DTOcean, but unfortunately it was not possible to implement this within the DTOceanPlus project timescale. Therefore, this was logged as a potential future enhancement.

Energy Delivery does not consider the export cable landfall method, although LMO does give options of open cut trench or Horizontal Directional Drilling (HDD). This has also been logged as a future improvement to the tools.

Connector costs do not vary with voltage in the catalogue of electrical components provided with DTOceanPlus, as this information was not publicly available when the cost review was undertaken. As with all component costs, this can easily be updated in the catalogue by the user if they have more data. As noted during the DTOceanPlus tool demonstration [14], subsea hubs with dry-mate connectors could be included as an additional option. This is the case with EnFAIT where a dry-mate connection is used when intervention is occasional or unlikely.

As the connector type is set in Machine Characterisation in integrated mode, this would require that two separate projects be created to compare wet-mate and dry-mate options, or that this is compared using the ED module in standalone mode.

Only a summary of the bill of materials is presented in the ED results, with four totals for the array network, collection point, transmission network, and onshore infrastructure. It would be much more helpful to include a breakdown of component costs and quantities.

5.8 Station Keeping

5.8.1 Summary of tool and use cases

The Station Keeping (SK) module is used to design and assess moorings and foundations solutions.

For gravity foundations, the tool can design and assess simple cylindrical or cuboid foundations, plus three-contact-point foundations. It is understood that the tool only designs the seabed interface; any gravity base sub-structure is assumed to be part of the device specified in Machine Characterisation. This may cause issues with the installation operations planning in LMO, as discussed in section 5.9.

For floating devices, the tool designs mooring lines and anchors. It can also design monopile foundations. Neither of these functionalities was tested within the EnFAIT project, as they are not applicable at the Shetland Tidal Array.

5.8.2 Comparison with EnFAIT array

Discussions were held during the DTOceanPlus project between Nova and the module developers FEM regarding the design of gravity foundations for tidal turbines. The results produced by the SK tool are in line with expectations, i.e. mass required to stop overturning or slippage for the M100D turbines [14]. The design is more basic, considering just a single lump mass.

The contact-point foundation design output from the SK tool is rotationally symmetrical with 120° spacing, whereas the gravity base foundations used in the EnFAIT array are not, as shown in section 3.1.2. The result from the integrated mode assessment also has somewhat smaller dimensions than either the Nova M100 or M100-D foundations, likely as a result of the drag effects of the ballast not being iteratively considered.

5.8.3 Limitations and future improvements

A few limitations have been identified with how fixed foundations are designed in Station Keeping, no tests have been made with moored floating devices within the EnFAIT project.

Gravity foundations within Station Keeping do not consider any jacket or support structure, instead this is intended to be represented within the Machine. This however affects the Logistical operations in

LMO, increasing the crane and deck requirements and reducing the installation of the gravity base sub-structure and the turbine nacelle to a single operation. It would be useful to add more granularity to the design so that the approach used in the EnFAIT array could be more accurately represented.

The gravity foundation calculation implementation appears to be relatively simplistic. A future improvement would be if the tool undertook further iterations of the initial design to account for the self-induced drag of each calculated foundation design [14].

With regards to the tool inputs:

- As the foundation type is set in Machine Characterisation in integrated mode, this would require that two separate projects be created to compare gravity and piled foundation options, or that this is compared using the SK module in standalone mode.
- For piled foundations, the user must manually specify the height of pile above the seabed. It would be more useful to define this as height above mean sea level, again so that the logistical operations are more accurately represented.
- The foundation soil properties dialogue only has the options 'Dense sand' or 'custom'; it would be useful to include additional defaults.

The results presented in the Station Keeping module are somewhat limited:

- The bill of materials just lists 4 units of "gravity_foundation1", it does not give any further breakdown of material quantities etc.
- No graphical representation of the designed foundation is presented; however the overall dimensions and angles (where appropriate) are given.
- Each device design is presented separately on the design assessment page, making them more difficult to compare.
- The format of the output coordinates used in the API is unclear and not documented. They seem to be 6 degree-of-freedom translations and rotations, but where this is referenced to is not apparent.

5.9 Logistics and Marine Operations

5.9.1 Summary of tool and use cases

Logistics and Marine Operations (LMO) is used to design logistical solutions and operations plans related to the installation, operation, maintenance, and decommissioning operations. For the main components of the array designed by the previous modules LMO designs operations and selects appropriate vessels, equipment, and port terminals. It calculates O&M operations based on the component failure rates from previous modules. The operations are scheduled accounting for suitable weather windows. The results are output as a table of operations and visualised as a Gantt chart.

Due to the issues experienced running LMO in integrated mode, it has also been tested standalone. This however has meant that the assessment has been more limited than planned. Further testing and analysis of potential future logistical solutions for installation and O&M of larger arrays will be completed within the EnFAIT project using the LMO tool, to be reported in D10.6.

5.9.2 Comparison with EnFAIT array

In integrated mode, the LMO module does not accurately represent the EnFAIT array installation and maintenance operations. Although the LMO calculation logic should be relatively flexible, it was not possible to properly model the EnFAIT array using LMO integrated with the other DTOceanPlus tools due to the limitations with the catalogue module discussed in section 5.2.2. This appears to be compounded

by the fact the LMO module appears to be using the fall-back internal catalogue, which cannot be edited in this setup. To overcome this, a standalone version of LMO was installed and used as discussed below.

By default in integrated mode, the LMO solution uses more capable but expensive vessels for the array installation and maintenance. These are a propelled crane vessel for the foundation and device installation, retrieval, and redeployment, and a cable laying vessel for the cable installation, both installations supported by an ROV. The vessels are mobilised from the Ågotnes port in southwest Norway. In contrast, Nova have used a multicat vessel for all operations on the EnFAIT array operating from the nearby harbours of Cullivoe or Belmont in Shetland. The total duration predicted for these activities is also significantly longer than Nova's experience.

Due to the high failure rates from Energy Transformation, the maintenance solution calculated in integrated mode is not representative. For an array of 4 turbines, around 10 failures per year requiring repair at port are predicted, whereas the EnFAIT array turbines are now operating with shoreside servicing required every 18-24 months. This is predicted to reduce further following the learnings within the EnFAIT project. Note that after this assessment, the Energy Transformation code was updated to address the high failure rates.

For underwater installation operations, LMO requires either divers or an ROV, noting the former may have health and safety implications. Neither is used for the EnFAIT array, with operations monitored via underwater cameras a much lower cost solution. This should be added as an option within LMO.

Using standalone version of LMO

To overcome the limitations experienced running LMO integrated with the other tools, a standalone version of the tool was installed. The code was pulled from the GitLab repository¹⁷ and run using the GNU Make tool¹⁸ on macOS. With this version, it was possible to edit the tool's internal catalogue, which is stored within the code as a series of csv files. Several updates to the LMO tool were made during the testing within EnFAIT, as the LMO tool is being further developed by WavEC within the EU-SCORES project¹⁹.

By updating the terminals catalogue to additionally include Bluemull, Belmont and other nearby ports, the LMO tool then selected Bluemull as the optimal location for the installation and O&M activities.

An EnFAIT 'multicat only' operation solution was tested by removing all other vessels from the vessels catalogue, as it is not possible to directly select the vessel(s) to be used/considered. This multicat vessel did need Dynamic Positioning (DP) capabilities however, as this is apparently a hard-coded requirement within LMO for gravity foundation installation operations. Within the EnFAIT project however, the installation has been successfully carried out using a multi-point mooring.

The resulting operation durations still appear to be overestimated; however, a full assessment has not been completed at this time. Additional use and testing of LMO is planned over the next months.

5.9.3 Limitations and future improvements

It is not directly possible to select preferred equipment, vessels, ports, etc. for the operations; instead an optimised solution is always calculated based on the tool logic and catalogues values. By adjusting the items in the catalogues, it is possible to force the assessment selection. For example, considering

¹⁷ https://gitlab.com/dtoceanplus/dtop_lmo

¹⁸ <https://www.gnu.org/software/make/>

¹⁹ <https://euscores.eu/>, H2020 Grant agreement № 101036457.

only a multicat vessel for installation by removing all other vessel types and updating the vessel combinations catalogue. However, this process is suboptimal and not clear.

The positional inputs from EC and ED are specified as UTM coordinates, and SK uses an unspecified projected coordinate system. These are assumed to be WGS84 in LMO, but it appears only the results from EC are converted. The integration of coordinates from ED and SK should be corrected.

Within the installation solution Gantt chart, only a high-level overview of the operations is given. It would be useful to see more granularity, such as mobilisation/demobilisation times. Because of this, it is not clear whether mobilisation/demobilisation is included for every operation, or just once per vessel. If the former this should be updated where two operations occur consecutively. It would also be useful to be able to set the mobilisation time per vessel, which would allow solutions with a (semi)-dedicated vessel to be used for installation and/or O&M.

It is also not clear from the LMO O&M results which component/turbine has failed, although perhaps that level of detail is not necessary within the LMO tool if it is displayed elsewhere, e.g. RAMS.

For tidal energy, the resource follows a predictable pattern, with known periods around neap tides where the velocities are lower. It would be useful to be able to account for this in the scheduling of installation and preventative maintenance strategies, as this could both increase accessibility windows and minimise lost energy yield.

Memory limitations in Docker were encountered when testing LMO in integrated mode, with all modules installed and running in Docker. The LMO calculation was failing with an error 502 bad gateway. Troubleshooting with the module developer highlighted that one of the Docker worker processes was restarting after about 11 minutes, as shown in the final line of the log extract in Figure 5.7, triggering the error. Increasing the Docker memory limit to 12GB from the 8GB recommended in the DTOceanPlus documentation resolved these issues, but the cause or solution of this error was not clear.

```
[2022-01-18 16:02:38 +0000] [1] [INFO] Using worker: sync
[2022-01-18 16:02:38 +0000] [9] [INFO] Booting worker with pid: 9
[2022-01-18 16:02:38 +0000] [10] [INFO] Booting worker with pid: 10
[2022-01-18 16:02:38 +0000] [11] [INFO] Booting worker with pid: 11
[2022-01-18 16:02:38 +0000] [12] [INFO] Booting worker with pid: 12
[2022-01-18 16:13:52 +0000] [45] [INFO] Booting worker with pid: 45
```

Figure 5.7. Log extract from LMO, showing fifth worker booting after 11 minutes, caused by insufficient memory

5.10 System Performance and Energy Yield

5.10.1 Summary of tool and use cases

System Performance and Energy Yield (SPEY) is the first of the assessment tools. It is used to evaluate projects in terms of energy performance, collating the results from the design tools and calculating metrics. In integrated mode, SPEY gets the inputs directly from the design tools, however the user also has the option of using alternative inputs specified as a JSON file in the format of the relevant module output.

The module presents results in terms of efficiency, energy production, power quality, and alternative metrics, aggregated at a device and array level. There is also the option of downloading each page of requests in JSON format for further analysis externally.

5.10.2 Comparison with EnFAIT array

No comparison with the EnFAIT array was possible for SPEY, as the inputs from other modules are not representative, and thus would not be a fair assessment.

5.10.3 Limitations and future improvements

The SPEY tool can be run with only partial input from the design tools, with either the user adding the inputs for the modules not run or omitting the metrics that depend on missing modules. However, this functionality does not work if a design is started, but not complete, in any of the design tools. In this instance it is not possible to run the SPEY assessment.

Pop-up help information is provided on all metrics, although some of these should be expanded with additional details, e.g. array q-factor just gives “q-factor of the array” as the extended description, whereas it could more usefully specify this is an array interaction factor and give the definition.

While SPEY provides a comprehensive overview of the collated outputs, an improved graphical representation would add significant value. The current interface does not show by default any inputs at a device aggregation level, requiring the user to click to view each of these, as shown in Figure 5.8.



Figure 5.8. Example of SPEY results, only showing details per device after clicking (indicated by arrows).

5.11 System Lifetime Costs

5.11.1 Summary of tool and use cases

System Lifetime Costs (SLC) is used to evaluate projects from an economic perspective. It compiles a summary bill of materials for the project from the design tools. The overall economic performance (in terms of CAPEX, OPEX, LCOE) and financial attractiveness (as IRR, NPV) is calculated accounting for project lifetime, electricity market price, grant support, and feed-in tariff (FIT) support.

5.11.2 Comparison with EnFAIT array

No comparison with the EnFAIT array was possible for SLC as the inputs from other modules are not representative. This is particularly driven by the high failure rates that were incorrectly calculated in ET (although as noted in section 5.6 this bug was recently fixed). This was causing many maintenance interventions in LMO, resulting in an unrealistically high OPEX value. Some CAPEX and OPEX inputs also need refined in the catalogues to match Nova’s experience within the EnFAIT array. The outputs from SLC are however consistent with the inputs, and the module appears to function correctly.

5.11.3 Limitations and future improvements

The formatting/display of the compiled bill of materials could be improved by, for example, creating headings for each category, clarifying the names of each item, and the total rows could be highlighted with the NA removed. It could also be useful to either provide a more detailed breakdown of the materials used for each category, or link to the relevant breakdown in the specific design module. The current bill of materials is shown in Figure 5.9 with a suggested mock-up in Figure 5.10.

Project Bill of Materials						
ID	Name	Quantity	Unit of Measurement	Unit Cost	Total Costs	Category ~
Device	fixed	4	N/A	1000000	4000000	Device
Tot_Device	Device total cost	N/A	N/A	N/A	4000000	Device
Cat_ID_0	Direct_Tidal	4	NA	0	0	Device
Cat_ID_1	Elect_Simplified	4	NA	10000	40000	Device
Cat_ID_2	Grid_Simplified	4	NA	10000	40000	Device
Tot_Array	Total array network	NA	NA	NA	0	Grid
Tot_Collection_Point	Total collection point	NA	NA	NA	0	Grid
Tot_Onshore	Total onshore infrastructure	NA	NA	NA	0	Grid
Tot_Transmission	Total transmission network	NA	NA	NA	1157465	Grid
none	gravity_foundation1	4	unit	2356.194490192345	9424.77796076938	Moor_Found
Tot_Inst_Dev	Total cost of installation of devices	-	-	-	606230.81557935	Installation
Tot_Inst_Anc	Total cost of installation of Anchors	-	-	-	685182.1305913499	Installation
Tot_Inst_Cable	Total cost of installation of cables	-	-	-	577358.5546498164	Installation
Tot_Inst_Other	Total other costs	-	-	-	0	Installation

Figure 5.9. Example bill of materials output from SLC

Category	Name	Quantity	Unit of Measurement	Unit Cost	Cost	Total Cost
Device	fixed	4	unit	1,000,000.00	4,000,000.00	
	Direct_Tidal	4	unit	-	-	
	Elect_Simplified	4	unit	10,000.00	40,000.00	
	Grid_Simplified	4	unit	10,000.00	40,000.00	
	Device Total					4,080,000.00
Grid	Total array network	-	-	-	-	
	Total collection point	-	-	-	-	
	Total onshore infrastructure	-	-	-	-	
	Total transmission network	-	-	-	1,157,465.00	
	Grid Connection Total					1,157,465.00
Mooring & Foundation	Gravity foundation 1	4	unit	2,356.19	9,424.78	
	Mooring & Foundation Total					9,424.78
Installation	Total cost of installation of devices	-	-	-	606,230.82	
	Total cost of installation of Anchors	-	-	-	685,182.13	
	Installation Total					1,291,412.95
	Total Cost					6,538,302.72

Figure 5.10. Mock-up of a possible improved bill of materials output

It is also noted that the decommissioning costs do not appear in the project bill of materials, however as highlighted in [14] these are important to consider. If these are accounted for elsewhere this should be clarified.

It might be interesting to include provision for other support mechanisms such as Contracts for Difference (CfD), especially as tidal energy now has a ring-fenced support pot in the UK's fourth CfD allocation round [29]. However, this could be approximated as a FIT at the average revenue support from the CfD.

Under the benchmark metrics, a ratio between the project and benchmark value could be calculated to offer additional value and make these comparisons easier.

5.12 System Reliability, Availability, Maintainability, Survivability

5.12.1 Summary of tool and use cases

System Reliability, Availability, Maintainability, Survivability (RAMS), to evaluate these aspects of a marine renewable energy project. The RAMS assessments are summarised in Table 5.6.

Table 5.6. Main functionalities of RAMS assessments

Assessment	Main functionalities
Reliability	Component-level reliability assessment simulates time to failure (TTF) of basic components.
	System-level reliability assessment simulates the time to failure (TTF) of subsystems (energy delivery, energy transformation, and station keeping) and the array
	Calculates the maximum annual probability of failure (PoF) of these subsystems and the array
Availability	Calculates the availability of individual devices and the average availability of the array
Maintainability	Calculates the probability that the damaged components can be repaired within a specific period of time, given prescribed resources and equipment.

5.12.2 Comparison with EnFAIT array

Unfortunately, errors were experienced when running this tool in integrated mode, and it was not possible to test it. It was not clear whether the error was a result of the input values from other modules, or some other issue with the module.

5.12.3 Limitations and future improvements

When using the module in integrated mode, the user is presented with an error message warning of missing SK, ED and ET hierarchies for system and components. It is not immediately clear the user has to click the 'Fetch SK' button. Similar errors are shown until all three module's outputs have been fetched. If required, these should be shown as warnings rather than errors, with instructions on how to resolve.

When trying to run the module, the error messages received were unclear, and appeared to sometimes relate to previous tests. Reviewing the calculation logs suggested a float division by zero error as potentially to be the underlying issue.

Additional error checking of input data appears to be required to properly run and test this module.

Reviewing the documentation, the units for failure rate were not clear. In the electrical components' catalogues, these have units of failures/year or failures/km/year for cables, but the units are not clear for other items.

5.13 Environmental and Social Acceptance

5.13.1 Summary of tool and use cases

Environmental and Social Acceptance (ESA) is used to evaluate the environmental and social impacts of given wave and tidal energy projects. This evaluation covers four areas, although some only at higher complexity, as detailed in Table 5.7. Due to errors running ESA and earlier modules, there was limited time available to perform a full assessment and comparison with the EnFAIT array.

The module has extensive documentation, covering the complex multi-faceted assessments.

Table 5.7. ESA assessment areas and complexity levels

Assessment areas	Complexity Levels
1. Identification of the potential presence of endangered species in the area of MRE installation (i.e. species included in the IUCN red list).	1-3, Low/Medium/High
2. Environmental impact assessment estimated for the main environmental stressors pre-identified as potential stressors from MRE such as the underwater noise or the collision risk between vessels/devices and the marine wildlife.	2-3, Medium/High
3. Estimation of the carbon footprint and the green-house effect of the project in terms of Global Warming Potential (GWP) and Cumulative Energy Demand (CED).	3, High only
4. Information to improve the social acceptance of the project considering socio-economic opportunities.	3, High only

5.13.2 Comparison with EnFAIT array

For the endangered species assessment, ESA utilises the global species data from Site Characterisation, however as noted in section 5.3, this is of relatively low spatial resolution. The user has the option to manually add additional species. The outputs of the ESA endangered species assessment were compared with the Environmental Monitoring Reports prepared as part of the EnFAIT project in WP8 [30], [31]. Overall, there was low similarity in the species reported, although not all species observed at the EnFAIT array are endangered. Particularly, ESA did not highlight any species of birds, although endangered species are present.

The results of the EIA give negative and positive scores for a range of potential impact categories, together with a level of confidence, explanation, and recommendations.

Running the module at complexity 3 did not give any errors, but there were no outputs presented. It was not clear if this was caused by missing or incorrect inputs, or a bug with the software. It was therefore not possible to perform a full assessment of this module, as the carbon footprint and social acceptance are only assessed at complexity 3.

5.13.3 Limitations and future improvements

The endangered species assessment lists all species twice, with the second instance having a probability of presence of 999 which appears to be an error. This duplication should be removed.

ESA does not appear to be fully integrated with other modules, as it required user input of results calculated elsewhere. For example, LCOE is a user input for the ESA assessment, but it would be useful to have the value calculated in the SLC tool pre-populated in this input. Similarly, results of the logistical solution defined in LMO could be used. The ability to vary these in ESA to see the impact on the assessments without having to re-run all modules is useful, however.

When inputting the seasonal presence of receptors, it might be clearer for all months to be selected by default and the user deselects to indicate absence. This would be more consistent with the documented assumption of assuming presence if not explicitly specified.

Some of the inputs required are not fully clear, even with the section help and module documentation.

6 Overall assessment of DTOceanPlus

This section presents the overall assessment of the DTOceanPlus tools, starting with a recap of their functionality. The detailed assessment per module was covered in section 5, with points applicable to the entire suite of tools covered in section 4.

6.1 Recap of DTOceanPlus functionality

The DTOceanPlus suite of tools includes seven Deployment Design and four Assessment modules, which are described in section 2.2, and summarised below.

- Site Characterisation, to prepare metocean, geotechnical, and environmental data.
- Machine Characterisation, to characterise the prime mover, either WEC or TEC.
- Energy Capture, to optimise hydrodynamic performance at array level.
- Energy Transformation, to design power take-off and control solutions.
- Energy Delivery, to design electrical and grid connection solutions.
- Station Keeping, to design moorings and foundations solutions.
- Logistics and Marine Operations, to design logistical solutions and operations plans related to the installation, operation, maintenance, and decommissioning stages.
- System Performance and Energy Yield, to evaluate projects in terms of energy performance.
- System Lifetime Costs, to evaluate projects from the economic perspective.
- System Reliability, Availability, Maintainability, Survivability, to evaluate the reliability aspects of a marine renewable energy project.
- Environmental and Social Acceptance, to evaluate the environmental and social impacts of a given wave and tidal energy projects.

These are supported by a Main Module and Catalogues. The Design and Assessment tools allow a user to model the diverse aspects of a wave or tidal energy deployment in a holistic manner, considering the many and often conflicting requirements. Differing levels of complexity are possible in the DTOceanPlus tools, to account for varying stages of technology development and/or data availability.

DTOceanPlus also includes tools for technology innovation and development, although they were not used or assessed in the EnFAIT project. Structured Innovation, which provides processes to assist with concept creation, selection, and design. Plus a Stage Gate tool that uses metrics to measure, assess, and guide technology development. These could be particularly useful for earlier-stage technologies and projects, guiding progress towards deploying first devices and arrays.

DTOceanPlus has been substantially developed from the first-generation DTOcean tools, adding new functionalities, and addressing some of the limitations identified. Feedback from testing both DTOcean and DTOceanPlus within the EnFAIT project has contributed significantly to this. Compared with the original DTOcean, it is now possible to represent small tidal arrays more accurately in DTOceanPlus, better corresponding to the present status of the sector.

6.2 Comparison with EnFAIT

As with DTOcean, it was possible to build up a design and perform an assessment of an ocean energy project using the DTOceanPlus tools, although again some aspects deviated from the EnFAIT project. Many of the design parameters and results of these tools were reasonably similar to those from the EnFAIT array, however others differed substantially. It is again noted that some aspects such as reliability and environmental impact could not be fully assessed due to limited real-world experience and data, along with errors in running the tools.

During the assessment of the DTOceanPlus tools, it was not possible to accurately model all aspects of the EnFAIT array using the tools in integrated mode, primarily due to the limitations within the Site Characterisation module and some module integration bugs. Errors also occurred in other modules, particularly Energy Transformation, LMO, RAMS, and ESA which limited the comprehensiveness of the tools' assessment. Additional assessments have been carried out using the Energy Capture, Energy Delivery, and LMO modules in standalone mode, where it was possible to model most aspects of the EnFAIT array successfully.

The costs obtained with the DTOceanPlus tools were generally higher than Nova's experience, primarily a result of two factors. Firstly, discrepancies in the costs of components etc. included in the catalogues and default values. Secondly, from differences in equipment and processes selected, with DTOceanPlus for example assuming that more complex/specialised equipment and vessels were required for all marine operations. It is possible to refine most of the default values used within the tools and catalogues, which should result in closer cost estimates.

6.3 Issues identified with DTOceanPlus

There are, however, currently some issues to be addressed with the tools. These include errors where it is not clear if the user's input data is incorrectly specified/formatted, or if there is a bug in the code logic or integration between the modules. There are also aspects of the tools' scope along with assumptions/decisions made when coding the tools which may be suboptimal, a significant example being the large padding added to the lease area in Site Characterisation, but there are others with differing degrees of impact, collated in appendix A.2. It is noted that some of these issues would only become apparent through extensive testing of differing scenarios, as has happened in the EnFAIT project.

The Deployment Design tools produce an optimised design, although it is noted this optimisation only focuses on the scope of each individual module, due to the inherent difficulties in producing a globally optimised design considering the many factors involved. The user may need to consider multiple studies with the tools to develop a more globally optimised solution for their array/technology.

It would also be useful to give the user more ability to choose or fix parameters, rather than just produce an optimised design. For example, setting the location of the collection point/substation in Energy Delivery, or choosing the vessel(s) to consider in LMO. This is already possible in some of the tools, notably Energy Capture where the user can assess an input array or design an optimised layout.

The DTOceanPlus tools have comprehensive online documentation. This covers their use through a series of tutorials and how-to guides, offering step-by-step instruction on using the tools and achieving desired outcomes. Background and reference information is provided to give confidence in the tools' calculation logic. The code and API for the modules is also covered to assist with future development and debugging errors. However, there are several areas where this documentation is incomplete or unclear. Limitations with the documentation will be collated, and addressed where possible, within the EnFAIT project. Several updates have already been made to clarify and improve the documentation.

At present, a new user might struggle to install and then fully use the DTOceanPlus tools. Not all aspects of the tools are completely working at this point, however, plans are in place to address this. As noted previously, the DTOceanPlus documentation has been reviewed and updated within the EnFAIT project to make it clearer and more comprehensive, hopefully addressing some of the issues/ambiguity with the installation. Separately, discussions are ongoing between the partners of the DTOceanPlus project to review the limitations identified within the EnFAIT assessment, and consider any adjustments required to address these. This work should improve the tools to the point where they can be used more comprehensively, and further developed, by the ocean energy sector.

7 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 tools:

- **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.

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 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 Appendix B.3.

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 their 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 using specialised vessels with significantly higher costs, and always requiring an ROV or divers to monitor installation operations. Initially, very high failure rates were being calculated in the Energy Transformation module, but this error was recently resolved as part of the ongoing software development.

The assessments of both DTOcean and DTOceanPlus within the EnFAIT project has identified bugs, limitations, and potential areas for future development of these tools. Many of these are already resolved and/or incorporated into the DTOceanPlus tools as a result of the close collaborative working between the two projects. The outstanding potential improvements to the DTOceanPlus tools can be summarised into five categories as follows, with the full list of 67 points or themes provided in Appendix A. Only a minority of these point significantly impact the use of the DTOceanPlus tools, most are future enhancements some of which might be somewhat subjective.

- Software errors and integration inconsistencies between modules that need fixed. This should include improved error messages for the user and better handling of uncaught errors.
- Limitations in the scope of the tools and the design methodology adopted, plus some of the built-in assumptions may be suboptimal or require refinement.
- Improvements to the user interface, e.g. to improve consistency between modules, plus add more detail to the results and refine their presentation.
- Improvements/additions to the documentation, to help people use the tools and provide confidence in the underlying calculation methodology and assumptions used in the tools.
- Additional functionality that could be added to the tools that addresses other limitations found when testing with the EnFAIT array.

To facilitate the future refinement and development of the tools, these potential improvements are being logged as issues on the project's GitLab repository, as is standard for this type of open-source project.

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.

Discussions with those involved with the DTOceanPlus software development are ongoing, to prioritise improvements and work towards resolving them. In addition, as noted in section 4, 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, which will further improve their usability.

Future analysis within the EnFAIT project will further study several aspects of optimising future arrays using the DTOceanPlus tools. This analysis will focus on using the Energy Capture, Energy Delivery, and Logistics & Marine Operations tools. As well as the EnFAIT array at Bluemull Sound, other larger arrays including device agnostic cases will be considered. This will be reported in D10.6 DTOcean: Conclusion, presenting any lessons learnt, both for Nova and for the wider sector.

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Appendix A. List of potential future improvements to the DTOceanPlus Tools

The appendix collates the potential future improvements that have been identified as part of the assessment in the EnFAIT project reported in section 4. Note that this list may be somewhat subjective, is not an exhaustive list, and at this stage no prioritisation of importance or effort to implement has been assigned. Only a minority of these issues significantly impact the use of the DTOceanPlus tools; many are future enhancements to the tools, which could be added in their ongoing future development.

Some of these points are common to all, most, or only some of the modules, as noted in the following tables. The section(s) where these points are introduced in this report are also referenced.

A.1. Software errors and bugs

Any errors and bugs identified in the software should be fixed as soon as practicable. Those identified as part of the EnFAIT project are listed in Table A.1.

Table A.1. Software errors and bugs

Ref	Improvement/limitation identified – software errors/bugs	Module(s)	Section(s)
1.1	Clearer error messages need to be provided in the GUI throughout the tools, these should not automatically disappear after a few seconds. Where possible, they should advise the user on steps to resolve the error.	All	4.2
1.2	Fix errors with LMO catalogues	CM	5.2
1.3	The total velocity vector needs to be used when defining environmental conditions, not just U components.	SC	5.3
1.4	Resolve the discrepancy between download and upload formats for a machine in MC	MC	5.4
1.5	Add a warning before permanently deleting a machine	MC	5.4
1.6	Review and fix ‘Lease Area vertex’ integration error between SC & EC	SC, EC	5.5
1.7	Fix the display of the depth averaged velocity vectors to consider flood and ebb tides separately, rather than the average of all	EC	5.5
1.8	Fix the bug where captured/mechanical power higher than rated power is shown in ET [Already resolved]	ET	5.6
1.9	Fix the bug where marginally higher captured power is shown in ET cf. EC	ET (EC)	5.6
1.10	Resolve integration issues with LMO not correctly using catalogues, and not converting coordinates from ED and SK	LMO, CM, (ED, SK)	5.9
1.11	Fix any inconsistencies in input coordinates used in LMO	LMO	5.9
1.12	Review and fix divide by zero errors in RAMS, and associated error messages.	RAMS	5.12
1.13	Review and fix errors that prevent ESA running at complexity 3	ESA	5.13

A.2. Limitations of tool scope, design methodology and built-in assumptions

During development of the DTOceanPlus tools, choices were made regarding the design methodology used. There are also several built-in assumptions, that cannot be changed by the user. While this type of limitation is inevitable, some could be seen as suboptimal, and are listed in Table A.2. Some of these limitations could only be discovered after extensive use and testing, such as in the EnFAIT project.

Table A.2. Design methodology limitations

Ref	Improvement/limitation identified – design methodology	Module(s)	Section(s)
2.1	All Deployment Design modules must be run sequentially in integrated mode, it is not possible to skip or bypass a module with the user supplying data in the output format of that module.	All	4.2
2.2	Data stored separately for each module. An easy way to save/export and then load/import a project or study is needed. The Digital Representation may be a first step towards this, but it is not fully working.	All	4.2
2.3	Provide a way for the user to abort a calculation.	All	4.2
2.4	Differing conventions for handling user inputs from other modules, user interface, etc should be standardise where possible to make the tools more coherent.	All	4.2
2.5	Improve installation process to not need administrator rights nor accepting unsigned software, which may not be possible for some users. Clarify different versions on windows installer. Integrate installation of SC databases within the main installer, and provide warnings where components are not installed correctly.	MM	4.3
2.6	Requirement to use multiple projects to consider different sites or machines	MM, Docs	5.1
2.7	Update bathymetry outputs to provide more detail. Reduce excessive padding around the site lease area.	SC, (EC, ED)	5.3
2.8	Increase the number of probability bins used when simplifying the tidal velocity data and allow the user to select a reference point for this.	SC, (EC)	5.3
2.9	Allow a user to unlock and edit a machine (with appropriate warnings on data consistency)	MC	5.4
2.10	Allow the user to specify connector type in ED and foundation type in SK, as setting these in MC requires a new project and machine to assess different options	MC, ED, SK	5.4
2.11	Allow the user to model multi-part devices, with a separate foundation substructure and device nacelle/prime mover	MC, SK, LMO	5.4, 5.8, 5.9
2.12	Refine the cost assumptions for the electrical components, particularly connector costs in relation to rated voltage	CM, ED	5.7
2.13	Allow the user to specify preferred vessels, ports, etc. without deleting everything else from the catalogues	LMO, CM	5.9
2.14	Allow the user to supply inputs for modules where design is in progress, in addition to those where design is not present at all.	SPEY	5.10

A.3. User interface improvements

Some potential improvements to the user interface are summarised in Table A.3.

Table A.3. User interface improvements

Ref	Improvement/limitation identified – user interface	Module(s)	Section(s)
3.1	Make the calculation progress clearer to the user. A progress bar is not necessarily needed, but something like “step n of m” would be useful.	Most	4.2
3.2	Only provide outputs quoted to an appropriate level of precision	Most	4.2
3.3	Provide a means of simply exporting results in tabular format, for use in other analysis programmes.	All	4.2
3.4	Add in multiple layers of outputs on plots, e.g. bathymetry and resource on device/array layouts.	SC, EC, ED, SK	4.2
3.5	Make details such as level of complexity of an existing study clearer	Most	4.2
3.6	Provide more guidance/help on appropriate ranges/values of input parameters, this may also be addressed in the documentation (4.1)	Most	4.2
3.7	Make process of forking studies more intuitive/simpler for the user	MM	5.1
3.8	Consider rationalising the naming of entities, and removing required inputs	MM	5.1
3.9	Improved filtering functionality in catalogues	CM	5.2
3.10	Add more information to describe the machine inputs required, this might also be addressed in the documentation (4.4)	MC	5.4
3.11	Include device angle in the results from EC	EC	5.5
3.12	Clarify the default values used in the GUI and use device rated power instead of arbitrary 500kW. Improved the graphical presentation of the ET results.	ET	5.6
3.13	Provide a more detailed breakdown in the bill of materials, not just an entry for the total per subsystem	ED, SK, SLC	5.7, 5.8, 5.11
3.14	Add the ability to view and compare results for multiple foundations in SK	SK	5.8
3.15	Show more details/granularity in the results of LMO	LMO	5.9
3.16	Provide improved graphical/tabular presentation of result in SPEY. This should include refined descriptions/definitions of metrics.	SPEY	5.10
3.17	Improve the formatting of the SLC bill of materials, plus clarify/include decommissioning costs. Include ratios between project and benchmarks.	SLC	5.11
3.18	Remove error messages when loading module before other data is loaded	RAMS	5.12
3.19	Further integrate outputs from other modules into ESA inputs. Refine input of seasonal presence of receptors. Improve definition of inputs in the section help pages.	ESA	5.13

A.4. Improvements to the documentation

Some sections of the documentation are incomplete or unclear, as summarised in Table A.4. In addition to this, a full review of the documentation has been completed as part of the EnFAIT project, and updates will be made where possible to address any shortcomings found.

Table A.4. Improvements to the documentation

Ref	Improvement/limitation identified – documentation	Module(s)	Section(s)
4.1	Provide more guidance/help on appropriate ranges/values of input parameters, this may also be addressed in the GUI (3.6)	Most	4.2
4.2	Update all sections of the documentation that are incomplete or marked as draft	Most	4.2
4.3	Provide more details on environmental conditions for the SC reference sites and the required structure for the NetCDF input data files	SC	5.3
4.4	Add more information to describe the machine inputs required, this might also be addressed in the user interface (3.10)	MC	5.4
4.5	Update the Q-factor plot to show more precision in the quoted numbers	EC	5.5
4.6	Improve the documentation of the energy transformation steps, and how the user can address the fact the module is very sensitive to user inputs	ET	5.6
4.7	Define the format of the output coordinates from SK	SK	5.8
4.8	Define the failure rate units more clearly	RAMS, CM	5.12

A.5. Additional functionality

Finally, some additional functionality that could be added to the tools is covered in Table A.5.

Table A.5. Potential additional functionality that could be added

Ref	Improvement identified – additional functionality	Module(s)	Section(s)
5.1	Within SC, allow the user to upload and work with bathymetry data in UTM coordinates	SC, (EC, ED, SK)	5.3
5.2	Allow the user to use a combination of their own and reference/example environmental data.	SC	5.3
5.3	Allow user to upload pre-processed gridded environmental data	SC	5.3
5.4	The ability to click the site layout to add/reposition device, rather than just typing coordinates	EC	5.5
5.5	Consider allowing the user to specify generator losses as a load/efficiency curve	ET	5.6
5.6	Allow the user to model generators at voltages other than 690V in ET, and include the option/assessment of voltage transformation on the device	ET, ED	5.6, 5.7
5.7	Improve cable routing algorithm to consider spacing between cables, cable crossings, and positioning relative to devices.	ED	5.7
5.8	Investigating caching partial results to speed up multiple calculations	ED	5.7
5.9	Add the ability to manually specify the collection point location	ED	5.7
5.10	Refine the gravity base foundation algorithm to account for self-induced drag and the pile foundation design to automatically account for water depth	SK	5.8
5.11	Add additional default soil properties	SK	5.8
5.12	Consider operations scheduled around neap tides	LMO	5.9
5.13	Add in ability to consider/assess other support mechanisms, such as CfD	SLC	5.11

Appendix B. Assessment of DTOcean design tools (v1.0, v2.0)

This appendix covers the previous assessment of the first-generation DTOcean tools, conducted between Oct. 2017 and June 2020. Firstly recapping the initial assessment of DTOcean v1.0, previously published as D10.3 and D10.4, then summarising the more detailed assessment which also considered DTOcean v2.0.

During the assessment of DTOcean, a second-generation suite of tools was developed within the DTOceanPlus project (which included both The University of Edinburgh and Nova Innovation as partners). Therefore feedback from using DTOcean within the EnFAIT project was passed directly to the teams developing the new software.

The results of the assessment of DTOcean are provided for completeness; the most up-to-date assessment of the more recent DTOceanPlus tools is covered in sections 4–6.

B.1. Recap of initial assessments

Within the EnFAIT project, an initial assessment of the DTOcean tools was reported in D10.3 DTOcean: Scenario Definition & Performance Metrics [17]. This focused on the first three design themes (Hydrodynamic, Electrical and Foundation). The assessment of the final two design themes (Installation and O&M) and three assessments (Economics, Reliability and Environmental) and overall assessment was reported in D10.4 DTOcean: Comparative with Design [18]. A series of recommendations were also provided for the future development of the tools.

For each module, 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. A summary of the parameter similarity comparisons made in the initial assessments is presented in Table B.1. Note that 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.

Table B.1. Summary of initial assessment parameter comparisons [17], [18]

Parameter	Numerical model (DTOcean)	Existing array (theoretical)	Similarity Classification	Module Classification
Hydrodynamics module				
Array AEP	102%	100%	High	Medium
Turbine locations	Distributed across whole lease area	Concentrated to south of lease area	Medium	
Array orientation	General array orientation	Different for each turbine	Medium	
Electrical module				
Cable route	One collector cable	One cable per turbine	Low	Low
Offshore substation	Substation	No substation	Low	
Cable installation	Cutting	Surface laying	Low	
Mooring & Foundations module				
Device foundation type	Gravity	Gravity	High	Medium
Device foundation mass	71%	100%	High	
Substation foundation type	Pile	Gravity (for future stages)	Low	

Parameter	Numerical model (DTOcean)	Existing array (theoretical)	Similarity Classification	Module Classification	
Installation module					
Port selection	Cullivoe	Cullivoe & Belmont	Medium	Medium	
Vessel selection	Foundations	One (CSV)	One (Multicat)		Low
	Static export cables	Multiple (CLB, Tugboat, Multicat)	One (Multicat)		Low
	Device installation	Multiple (CSV and Multicat)	One (Multicat)		Low
Equipment type selection	ROV, Cable burial, Drilling rigs	Cable reeler	Low		
Main installation tasks	Foundation, Collection point, Cables, Device	Foundation, Cable, Device	Medium		
Preparation time	Foundation	40%	100%		Medium
	Cables	665%	100%		Low
	Devices	165%	100%		Medium
Departure delay	Foundation	600%	100%		Low
	Cables	700%	100%		Low
	Devices	1800%	100%		Low
Transit time	Foundation	8%	100%		Low
	Cables	100%	100%		High
	Devices	70%	100%		High
Waiting time	Foundation	100%	100%		High
	Cables	100%	100%		High
	Devices	100%	100%		High
Operation time	Foundation	240%	100%		Low
	Cables	680%	100%		Low
	Devices	400%	100%	Low	
Vessel cost	Costs include for multiple vessels	Confidential	Medium		
Equipment cost	Costs include for extra equipment	Confidential	Medium		
Operation and Maintenance module					
OPEX	Higher than Nova forecasts	Confidential, but needs more years of data	N/A	N/A	
Downtime of devices	Insufficient granularity of results	Insufficient operational data available	N/A		
Downtime of the array	Insufficient granularity of results	Insufficient operational data available	N/A		
Lifetime energy production	100%	100%	High		
Maintenance strategy	—	—	Medium		
Activities order	—	—	Low		
Economic Assessment module					
CAPEX	—	—	Medium	Low	
LCOE	Non-standard discounting calculation	—	Low		

Parameter	Numerical model (DTOcean)	Existing array (theoretical)	Similarity Classification	Module Classification
Reliability Assessment module				
System MTTF	Note: device reliability not assessed	More array operational data required to make an assessment	N/A	N/A
Export cable MTTF	—		N/A	
Moorings & Foundations Subsystems/device MTTF	—		N/A	
System reliability at mission time	DTOcean does not appear to include increased reliability due to maintenance		N/A	
Environmental Assessment module				
Footprint	Qualitative (high/medium/low) ranking might be more suitable than quantitative scores (+50/-100) for the environmental impact scores (EIS). Only considers results from hydrodynamics	More array operational data required to make an assessment, but some outputs broadly similar	N/A	N/A
Collision risk			N/A	
Collision risk vessel			N/A	
Energy modification			N/A	
Noise (underwater)			N/A	
Electric fields			N/A	
Magnetic fields			N/A	
Chemical pollution			N/A	
Turbidity			N/A	
Temperature modification			N/A	
Reef effect			N/A	
Reserve effect			N/A	
Resting place	N/A			
Recommendations	—	—	N/A	

B.2. Detailed assessment of DTOcean

No deliverables were scheduled during the detailed assessment of DTOcean. Therefore, a series of five 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 as well as 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, so these could be improved in the DTOceanPlus project. The advantages of the DTOcean tools were extensively discussed in the reports mentioned above [17] and [18].

The detailed assessment investigated three array layout cases: (1) Nova Innovation Design 1 (large array spacing), (2) Nova Innovation Design 2 (close array spacing), and (3) DTOcean Optimum Design (using the optimisation routine by DTOcean), see section 3.1.1 for (1) and (2). Several input parameters were varied during the study to assess the output sensitivity of the DTOcean tools. The study highlights only the results deemed to provide significant recommendations to external partners.

B.2.1. Hydrodynamic module

This section summarises the technical note DTOcean: Detailed Assessment (Hydrodynamic Module) [32], issued to the EnFAIT and DTOceanPlus project partners in January 2020. It is important to recall that the technical note highlighted the limitations and areas for improvement of the Hydrodynamic module. In addition, the advantages of the module were extensively discussed in report [17].

Input parameters such as the array layout configuration, tidal series, power curve, extraction points and probability bins were varied during the assessment to evaluate the module's sensitivity. Key output parameters from the DTOcean Hydrodynamic module that were assessed include the Capacity Factor (CF), Annual Energy Production (AEP) and Array Interaction (q-factor).

The optimisation routine for the DTOcean hydrodynamic module appears to be based only on minimising the array interaction q-factor, not on maximising AEP or minimising LCOE. Turbines were placed further apart and thus into areas of lower flow velocity, limiting the power output.

DTOcean 2.0 failed to run simulations with a fully representative tidal series, with detailed bathymetry and spatial variation in the flow. The module provided limited information of the failure, only giving an "irrotational flow error". This may have been caused by the input data not being formatted correctly. A simplified input that was spatially uniform with reduced bathymetry spacing was instead tested. Hence, the tidal series used by the Hydrodynamic module may not have been sufficiently representative to produce accurate results for AEP and CF.

The detailed assessment produced different hydrodynamic results from DTOcean v1.0 and v2.0 in terms of AEP and CF. DTOcean 1.0 produced significantly lower results, and DTOcean 2.0 results were slightly higher, when compared to manual power calculations and the expected values reported by Nova Innovation.

B.2.2. Electrical module

This section summarises the technical note DTOcean: Detailed Assessment (Electrical Module) [33], issued to the EnFAIT and DTOceanPlus project partners in January 2020. It is important to recall that the technical note highlighted the limitations and areas for improvement of the Electrical module. In addition, the advantages of the module were extensively discussed in report [17].

Input parameters such as the network configuration, maximum number of devices per radial string, type of connectors, export cable voltage, burial depth and different array layouts were varied during the assessment to evaluate the module's sensitivity. Key output parameters from the DTOcean Electrical module assessed include the cable route, electrical bill of materials, CF, and network efficiency.

The Electrical module suggested an "optimal" solution for the electrical infrastructure for each array layout, such as cable routes and substation position. However, for some of the cases assessed, the inter-array cabling route suggested by the module was not optimal. Some of the solutions resulted in longer than necessary intra-array cable routes or placing the hub too close to the turbine than is safe or practical.

The CF calculation in the DTOcean (v1.0 and v2.0) electrical module appears to be incorrect; it gives higher results than calculated in the Hydrodynamic module. This therefore gives an over-estimate of the network efficiency, which gets capped at 100%. It is important to check the integration between the various modules, with a wide range of test cases. The detailed assessments of DTOcean 1.0 and 2.0 therefore could not compare the network efficiency and CF results with the expected values reported by Nova Innovation.

It was not possible to test the electrical module independently of the other modules, to explore the CF discrepancy further. This could be a useful additional functionality.

Regarding the network configurations, the Electrical module ran with a radial arrangement. However, DTOcean (v1.0 and v2.0) did not run with a star network configuration; the module returned varying error messages with no apparent reason for the failure. Neither version was able to model the direct cables to shore used in the EnFAIT array.

B.2.3. Foundation module

This section summarises the technical note DTOcean: Detailed Assessment (Foundation Module) [34], issued to the EnFAIT and DTOceanPlus project partners in February 2020. It is important to recall that the technical note highlighted the limitations and areas for improvement of the Foundation module. In addition, the advantages of the module were extensively discussed in report [17].

Input parameters such as the current directions, foundation location, system dimensions and mass and number of foundations per device were varied during the assessment to evaluate the module's sensitivity. Key output parameters from the DTOcean Foundation module include the foundation type, foundation bill of materials and foundation components supplementary data.

For the same inputs, DTOcean 1.0 and 2.0 provided different results, but the cause of these discrepancy was not fully clear. The logic of the optimisation routines was not fully clear within the tool or documentation. The coordinate system used for the inputs to the module was also not clear.

A sensitivity assessment varying the total system mass with gravity foundations in DTOcean 1.0 produced no variation in the output, which is not as expected. The system mass results provided by DTOcean 2.0 were closer to the Nova Innovation values.

In some instances with DTOcean 2.0 when the user selected the gravity type foundations and the structure weight alone is sufficient, no additional foundation should be required; however a pile foundation was specified in the design. This added additional costs, and thus was not an optimal solution.

The results for gravity foundations were not clear as to the materials used. Some used concrete only, other a concrete/steel composite structure, but the proportions of each material were not given. This was also not clear within the documentation.

Some of the code functionality in DTOcean 1.0 does not follow the documentation provided in the related deliverables from the project. It is important to have clear and accurate documentation for all functionalities.

B.2.4. Installation module

This section summarises the technical note DTOcean: Detailed Assessment (Installation Module) [35], issued to the EnFAIT and DTOceanPlus project partners in May 2020. It is important to recall that the technical note highlighted the limitations and areas for improvement of the Installation module. In addition, the advantages of the module were extensively discussed in report [18].

Input parameters such as the installation start date and multicat vessel library order were varied during the assessment to evaluate the module's sensitivity. Key output parameters from the DTOcean Installation module assessed include the installation end date, installation time, vessel selection and installation costs.

The remarks made here were observed in both DTOcean versions.

Concerning the installation start date, the module presented identical total costs and total time for different scenarios regardless of the installation duration, excluding waiting times from the total calculations. This could be due to the assumptions made by the module; however, these were not made clear by the documentation.

The installation time given by the module was significantly higher compared with Nova Innovation's real experience with the existing array deployed in the Shetland Islands. This is compounded by the sequence and duration of the logistical operations being hard coded in the module, where it is not possible for the user to edit.

There was no information provided, apart from costs, regarding what equipment was used for each component installation. Therefore it was difficult to assess this.

The Installation module determined the multicat support vessel(s) based solely on cost, disregarding physical and environmental feasibility checks, such as size and weather limitations. So, the module selected the first cheapest listed vessel in the DTOcean Library, discounting other operation requirements.

The device subcomponents and installation steps were executed sequentially in the module; the foundation structures were deployed, the collection point was installed, cables were installed, and finally, the devices were installed. DTOcean only selects a weather window that is sufficient to complete the whole sea time of each component in one go. DTOcean has a lack of ability to break the work down into smaller packages of work or to consider tidal windows. These assumptions do not align with Nova's experience, where shorter weather windows are used to complete the logistical steps in smaller chunks. The Installation module does not allow the user the flexibility concerning the order of the installation steps.

With reference to the GUI, the port selected was shown, but neither the vessel(s) nor the equipment selected were shown in the GUI. Therefore, it was not clear to the user which vessel or combination of vessels was chosen to install each component. Some details were only displayed in the 'system dock' log box. The module also used different labels for the tables and graphs generated regarding the installation time, which the user might misunderstand.

B.2.5. O&M module

This section summarises the technical note DTOcean: Detailed Assessment (O&M Module) [36], issued to the EnFAIT and DTOceanPlus project partners in June 2020. It is important to recall that the technical note highlighted the limitations and areas for improvement of the O&M module. In addition, the advantages of the module were extensively discussed in report [18].

Input parameters such as the calendar/condition-based maintenance, subsystem operations and device operation weightings were varied during the assessment to evaluate the module's sensitivity. Key output parameters from the DTOcean O&M module that were assessed include the vessels and equipment selected, best/worst-case calendar/condition-based maintenance events tables.

Only the DTOcean 2.0 O&M module was tested, as this includes the additional functionality of iterations to be considered when calculating the most likely values. Without this, in DTOcean 1.0, the user would need to manually re-run the tool multiple times.

Due to the limited operational data available at the time of the assessment, it was not feasible to evaluate the similarities between the O&M module of the DTOcean and Nova Innovation's experience with the real-world deployment. However, the OPEX estimation by the O&M module was higher than Nova Innovation's estimates. Some comments from assessing the tools' functionality are given below.

- The results seem unrealistic and overconservative when Calendar Based Maintenance is activated with more than one operation type (On-site Maintenance, Inspection and Replacement). In one case, the PTO for all devices was replaced, and then inspected and maintained 11 days later.
- The Condition Based Maintenance function did not work, resulting in an error.
- The downtime associated with some activities shows a value of zero hours, which looks to be a bug.

As with other modules, some of the values, including such as logistic steps (sequence), operational time for components O&M as well as equipment selected, are hard-coded and cannot be modified by the user.

Some details were only displayed in the 'system dock' log box, others including the equipment selected is not displayed at all. It would be useful both to include this within the GUI and to allow the user to export all module outputs into external formats.

The module's documentation does not provide a clear explanation of how inputs and functions relate to the outputs and the purpose of each operation type and how they relate to the Event Tables.

B.3. Overall assessment of DTOcean design tools

The DTOcean tools offer a holistic assessment of the multi-faceted process of optimising the layout of arrays of wave and tidal energy converters. This is conducted using a series of modular tools covering five design stages and three thematic assessments:

1. Hydrodynamics
 2. Electrical
 3. Moorings and foundations
 4. Installation
 5. Operations & maintenance
1. Economic assessment
 2. Reliability assessment
 3. Environmental impact assessment

It was possible to perform an assessment of an ocean energy project using the DTOcean tools, although some aspects deviated from the EnFAIT project. The design parameters and results of these tools were found to have a medium-low similarity to those from the EnFAIT array. It is noted, however, that some aspects such as reliability and environmental impact could not be fully assessed due to limited real-world experience and data.

The scope and intention of the original DTOcean tools (v1.0 & v2.0) was for planning and assessing commercial scale wave and tidal energy arrays. As part of the EnFAIT project, an assessment was carried out as to how well the tools can model small tidal projects, such as Nova's Shetland Tidal Array.

Due to some of the assumptions made within the DTOcean calculation and optimisation routines. These tools were not fully able to model the EnFAIT array. They are more focussed on design of larger-scale arrays, which is not yet aligned with the status of the sector.

For example, the hydrodynamic module optimisation aims to minimise array interaction, not maximise AEP. For small arrays, siting the turbines in the best resource could be more important than minimising the overall array interaction.

Similarly, the electrical module always assumes an offshore substation, which is not the case for either of the tidal arrays installed to date: 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, which it is not possible to model in DTOcean. The vessels selected for the installation are also significantly larger and more expensive than Nova's experience on the EnFAIT array.

In several instances, the error messages produced by the tools were unhelpful or inconclusive. It was therefore recommended that better error messages be provided to enhance the usability of the tools. Similarly, all results should be displayed in the GUI, rather than just appearing in the “system dock” log.

Another key finding was to make the documentation of the tools and calculation algorithms as clear and comprehensive as possible, to give users confidence in the tools. These should cover what was actually implemented, rather than the plans or aspirations. Having documentation, manuals, and technical background split across multiple documents makes it harder to use and comprehend.

The limitations identified with the tools were collated and used to improve the second-generation design tools in the DTOceanPlus project. Feedback from the extensive use and testing of DTOcean (v1.0 and v2.0) within the EnFAIT project was collated into a list of over 80 points. This was disseminated to the DTOceanPlus coding teams to improve these tools, and many of these issues were implemented or were otherwise resolved within the DTOceanPlus project.

B.3.1. Software obsolescence issue with DTOcean tools

It is noted that the DTOcean tools are coded in Python 2, which is no longer supported as of 1 January 2020 [7]. No new improvements or bugfixes will be released for Python 2, even for critical security issues. This does not prevent Python 2 code or tools using Python 2 from being run, but it could present a security risk if critical bugs are identified.

Therefore any future development of DTOcean 2 should consider upgrading to Python 3. This was highlighted as highest priority in the Sandia evaluation of the DTOcean toolset [37] (see below). Similarly, the GUI for DTOcean v2.0 was developed using the now obsolete ‘PyQt4’ framework, again, no longer supported. Both issues were estimated as ‘high’ effort level, corresponding to around two months of developer time (provided they are familiar with the code).

During testing of DTOcean v1.0, several issues were experienced when trying to install the software on additional computers. This may have been related to incompatible Python package dependencies, but this was not clear. Eventually it became impossible to install DTOcean v1.0, however this was resolved with the release of DTOcean v2.0. No further testing of DTOcean has been undertaken since June 2020, so it is unknown if installation is again problematic many months after the release.

B.3.2. Sandia National Laboratories evaluation of DTOcean v2.0

Separately to the EnFAIT project, Sandia National Laboratories released an evaluation of DTOcean v2.0 in October 2018 [37]. This introduced the tools then performed an assessment of two projects using the US Department of Energy (DoE) Reference Model Project (RMP), namely the RM3 floating wave energy converter and RM1 fixed tidal energy converter, reported in [19]. Overall, a good agreement was found between DTOcean and the RMP, although with some discrepancies. This evaluation of DTOcean does note however, that some design features could not be implemented or required a proxy in DTOcean.

This evaluation of DTOcean v2.0 also provided a prioritised list of 39 issues with, and improvements to, the DTOcean software, which cover:

- **Software implementation** – Updating to code to Python 3 and GUI framework to PyQt5, adding support for multiple processors and other design module efficiencies, and improving the code quality and unit testing. The representation of variability to address uncertainty quantification could also be added, but thus would require considerable remodelling of the tools.
- **User experience** – Improving the documentation and tutorials. Providing graphical tools to work with the database, and other tools to help manage the complex inputs. Reorganise and simplify the user inputs, along with providing sensible default values where possible. Provide additional results,

and restructure these to be clearer. Finally, currency conversion would make the tool more globally applicable.

- **Modelling** – recommendations per module:
 - *Hydrodynamics* should consider bathymetry effects in wave energy calculations and fix the external forces provided to the moorings and foundations calculations.
 - *Electrical Subsystems* should include additional network configurations, better cable routing including crossing avoidance, and additional substation design.
 - *Moorings and Foundations* should consider bi-directional forces on turbine foundations, better calculation of the moorings on the first device, analysis of devices with integral foundations such as RM1, and better use of sediment layers data.
 - *Logistics* with multiple ships operating in parallel, consider operational limits in smaller tasks, and allow the specification of a designated vessel.
 - *Installation* to include multiple phases for large arrays
 - *Reliability* should be impacted by physical impacts of where components are installed. Validated models of components should be created where data is not available or commercially sensitive.
 - *Maintenance* should consider the failure of a single nacelle of a 2-turbine device, and better model failures of electrical networks. The calendar-based maintenance does not handle mixed failure modes correctly. Additional failure modes, control strategies, and optimisation of the maintenance strategy could all be added.
 - *Economics* only considers external costs as a lump sum, which could be itemized.
 - *Environmental* assessment should be more integrated with the design module outputs, and mitigation costs could be included in the LCOE calculation.
 - *Core* could be updated to allow automated array optimization.
 - *Database* could be improved with improved reference component data.

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