# Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment

## Deliverable D5.4

## Energy Transformation tools – Alpha version

| | |
|---|---|
| Lead Beneficiary | Tecnalia |
| Delivery Date | 13/05/2020 |
| Dissemination Level | Public |
| Status | Released |
| Version | 1.0 |
| Keywords | Energy Transformation, PTO, Mechanical transformation, Electrical Transformation, Grid conditioning, ET, DTOcean, DTOceanPlus |

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 785921

### Disclaimer

### Document Information

| | |
|---|---|
| **Grant Agreement Number** | 785921 |
| **Project Acronym** | DTOceanPlus |
| **Work Package** | WP5 |
| **Related Task(s)** | T5.5 |
| **Deliverable** | D5.4 |
| **Title** | Energy Transformation tools – Alpha version |
| **Author(s)** | Joseba Lopez-Mendia, Imanol Touzon, Eider Robles, Javier Lopez-Queija (Tecnalia), Jillian Henderson (Wave Energy Scotland), Francesco Ferri (Aalborg University) |
| **File Name** | DTOceanPlus_D5.4_Energy Transformation_alpha_20200513_v1.0.docx |

### Revision History

| Revision | Date | Description | Reviewer |
|---|---|---|---|
| 0.1 | 27/02/2020 | Initial structure and partial contents | Tecnalia |
| 0.5 | 16/04/2020 | Full draft for partners review | T5.5 partners |
| 0.7 | 27/04/2020 | Version for QA review | Inès Tunga, Despina Yiakoumi (ESC) |
| 0.8 | 12/05/2020 | Version for final review | Inès Tunga (ESC), Pablo Ruiz-Minguela (Tecnalia) |
| 1.0 | 13/05/2020 | Final released version for the EC | EC |

# EXECUTIVE SUMMARY

Deliverable D 5.4 "Energy Transformation tools – Alpha version" of DTOceanPlus project includes the details of the development Design tool module: "Energy Transformation" (ET), and it represents the result of the work developed during tasks T5.2 and T5.5 of the project.

This document serves as the technical manual of the alpha version of the ET module. It includes all the data requirements, main functions, interfaces and all the pertinent technical details describing the alpha version of the module for the Energy Transformation of an array of Wave Energy Converters (WEC) or Tidal Energy Converters (TEC).

This document describes the use cases and the functionalities, as well as the more technical aspects of the code implemented for the alpha version of this module. The ET module is built to be used as a standalone tool or within the framework of design tools of the DTOceanPlus project. It will offer two main design modes, a simplified design mode to give an estimate of costs and performance at an early stage, and a full design mode for later in the device/project development path

The Business Logic, i.e. the core functions of the ET module, has been implemented in Python 3. The code is provided with an Application Programming Interface (API), developed following the Open API specifications. A basic Graphical User Interface (GUI) for the ET module was developed using Vue.js, allowing the user to interact easily with the module, inputting data and visualizing the results. The Business Logic of the code was verified through the implementation of unit tests, guaranteeing easy maintainability for future developments of the module. The preliminary tests and verifications performed are presented. A section of this report is dedicated to examples, showing the capabilities of the tool for the wave and tidal energy converters at various levels of complexity.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AATE | Array Annual Transformed Energy |
| AEP | Annual Energy Production |
| API | Application Programming Interface |
| CPL | Level of Complexity |
| EC | Energy conversion |
| ED | Energy Delivery |
| EIA | Environmental Impact Assessment |
| ET | Energy transformation |
| ESA | Environmental and Social Acceptance |
| GUI | Graphical user interface |
| HTTP | Hypertext Transfer Protocol |
| ID | Identifier |
| IGBT | Insulated Gate Bipolar Transistor |
| LCA | Lifecycle costs assessment |
| LMO | Logistics and Marine Operations |
| MC | Machine Characterization |
| O&M | Operation and maintenance |
| ODE | Ordinary Differential Equations |
| OEM | original equipment manufacturer |
| OES | Ocean Energy Systems |
| PTO | Power take off |
| RAMS | System Reliability, Availability, Maintainability, Survivability |
| REST | Representational State Transfer |
| RMS | Root Mean Square |
| SC | Site Characterization |

| | |
|---|---|
| SCIG | Squirrel Cage Induction Generator |
| SG | Stage Gate |
| SI | Structured Innovation |
| SK | Station Keeping |
| SLC | System Lifetime Costs |
| SPEY | System Performance and Energy Yield |
| TEC | Tidal Energy Converter |
| UML | Unified Modeling Language |
| WEC | Wave energy converter |

# 1. INTRODUCTION

Deliverable D5.4 "Energy Transformation tools – Alpha version" of DTOceanPlus [1] project includes the details of the Deployment Design tools module: "Energy Transformation" or ET, and it represents the result of the work developed during the task 5.2. and 5.5

This document serves as the technical manual of the alpha version of the ET module. It includes all the data requirements, main functions, interfaces and all the pertinent technical details describing the alpha version of the module for the Energy Transformation of an array of Wave Energy Converters (WEC) or Tidal Energy Converters (TEC).

1. The **use cases and the functionalities** of the ET tools, namely providing the user with a set of relevant metrics and assessments pertinent to the performance of the different energy transformation steps.
2. The actual **implementation of the tool**, describing the architecture of the tool, the technologies adopted for the implementation and the results of the testing.
3. The **testing** of the code: The Business Logic of the code has been verified through the implementation of unit tests; therefore, the code can be easily maintained for future development.
4. A set of **examples**, that provide the reader with an overall view of the tools' capabilities.

## 1.1 SUMMARY OF THE DTOCEANPLUS PROJECT

The *Energy Transformation* module belongs to the suite of tools "DTOceanPlus" [1] developed within the EU-funded project DTOceanPlus. DTOceanPlus aims to accelerate the commercialization of the Ocean Energy sector by developing and demonstrating an open source suite of design tools for the selection, development, deployment and assessment of ocean energy systems (including sub-systems, energy capture devices and arrays) and at various levels of complexity (Early/Mid/Late stage).

At a high level, the suite of tools developed in DTOceanPlus as shown in Figure 1.1 will include:

- **Structured Innovation Tool (SI)**, for concept creation, selection, and design.
- **Stage Gate Tool (SG)**, using metrics to measure, assess and guide technology development.
- **Deployment Tools**, supporting optimal device and array deployment:
  - *Site Characterization (SC):* to characterize the site, including metocean, geotechnical, and environmental conditions.
  - *Energy Capture (EC):* to characterize the device at an array level;
  - *Machine Characterization (MC):* to characterize the prime mover;
  - *Energy Transformation (ET):* to design Power Take off (PTO) and control solutions;
  - *Energy Delivery (ED):* to design electrical and grid connection solutions;
  - *Station Keeping (SK):* to design moorings and foundations solutions;
  - *Logistics and Marine Operations (LMO):* to design logistical solutions operation plans related to the installation, operation, maintenance, and decommissioning operations.

- **Assessment Tools**, to evaluate projects in terms of key parameters:
  - *System Performance and Energy Yield (SPEY):* to evaluate projects in terms of energy performance.
  - *System Lifetime Costs (SLC):* to evaluate projects from the economic perspective
  - *System Reliability, Availability, Maintainability, Survivability (RAMS):* to evaluate the reliability aspects of a marine renewable energy project.
  - *Environmental and Social Acceptance (ESA):* to evaluate the environmental and social impacts of a given wave and tidal energy projects.

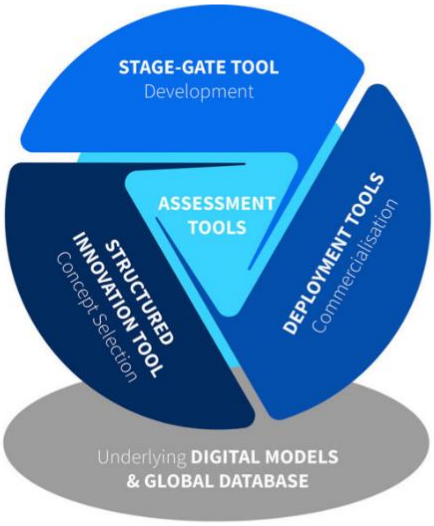


FIGURE 1.1: REPRESENTATION OF DTOCEANPLUS TOOLS

# 2. USE CASES AND FUNCTIONALITIES

The Energy Transformation module computes the transformation of energy from the power captured to the electrical output of each device in an array of Ocean Energy Systems (OES). In the energy conversion chain as illustrated in Figure 2.1, the Energy Transformation module is situated in between the Energy Capture (EC) and Energy Delivery (ED) modules. It allows the study of several Power Take-Off (PTO) systems both for tidal and wave energy converters focusing on the effect of various configurations, not only in terms of performance and costs, but also informs on the impacts on reliability, logistics and operation as well as possible environmental issues.

The Energy Transformation module has two overarching use cases: the analysis mode, where the user wants to assess a specific technology in a specific development stage and under a control strategy; or the design mode, where the main PTO characteristics are determined depending on performance and reliability factors.

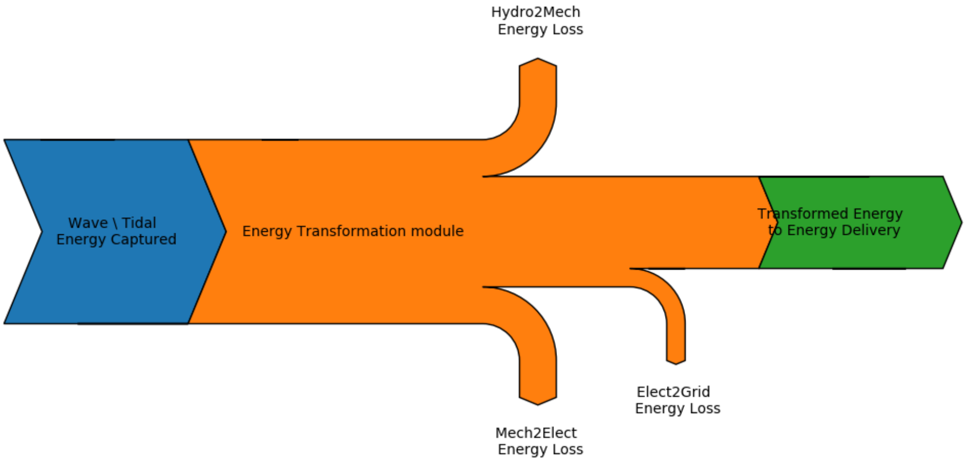


FIGURE 2.1: ENERGY FLOW REPRESENTATION IN THE ENERGY TRANSFORMATION MODULE

## 2.1 USE CASES

The Energy Transformation (ET) module designs the different energy transformation steps inside the device which can be executed at three different complexity levels each one. This section describes the main use cases of, and the functionalities implemented in the tool.

In this section, the use cases are described from an operational perspective, with respect to what the user decides to do, and which modules the user runs. The user is able to:

1. Run ET as part of the set of Deployment design tools of DTOceanPlus.
2. Run ET within the framework of the Stage Gate (SG) or Structured Innovation (SI) design tools.
3. Use ED in standalone mode.

## 2.2 USER GROUPS

Use cases depend on the user type and what they are looking for. Main targeted users of DTOceanPlus have been identified in the deliverable D2.1 [2] to be:

- Funders & Investors
- Innovators & Developers
- Project Developers
- Policy and regulators

From the Energy Transformation module perspective, eight examples of use cases have been identified as seen below in Table 2-1:

**TABLE 2-1: USE CASE IDENTIFIER**

| Use Case ID | User Type | Objective | Stage | Mode of Operation | Max/Min Function |
|---|---|---|---|---|---|
| 1 | Funders & Investors | Looking for a Technology | Early | Design | Cost |
| 2 | Funders & Investors | Assess specific technology | Mid | Analysis | |
| 3 | Innovators & Developers | Test a novel PTO | Late | Design | Performance |
| 4 | Innovators & Developers | Look for improvement areas | Mid | Design | Cost |
| 5 | Project Developers | Assess a PTO in a device | Mid | Design | Performance |
| 6 | Project Developers | Assess O&M implications of a PTO | Early | Analysis | |
| 7 | Policy & Regulators | Impact of a technology in the energy mix | Early | Design | Performance |
| 8 | Policy & Regulators | Environmental impact of a specific technology/site | Mid | Analysis | |

The architecture of the Energy Transformation module does not change with the mode of operation. However, the considered inputs change for different stages and modes of operation. A set of 6 different common base cases considered to illustrate the various tool possibilities:

1- Early stage & Analysis
2- Early stage & Design
3- Mid stage & Analysis
4- Mid stage & Design
5- Late stage & Analysis
6- Late stage & Design

Figure 2.2 shows how the 6 common base cases can represent all 8 use cases (more information at [3]):

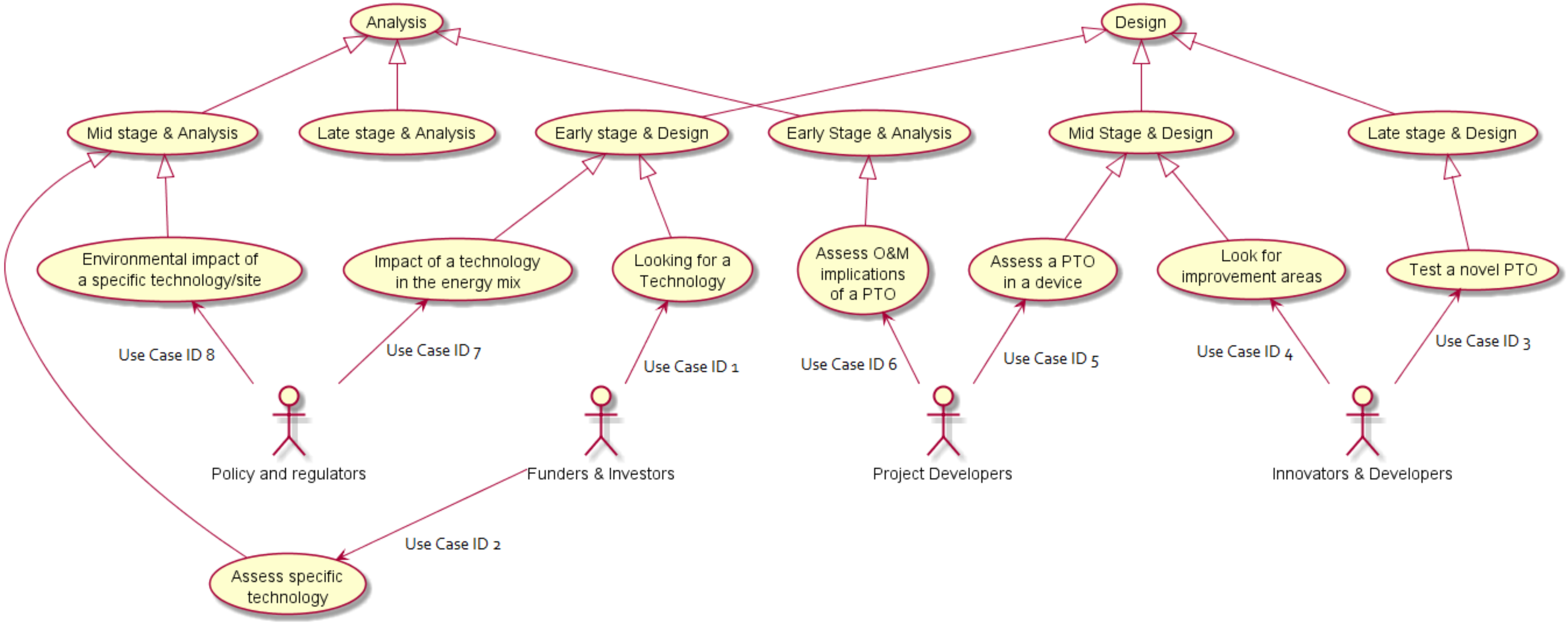


FIGURE 2.2: COMMON BASE CASES AS A FUNCTION OF DIFFERENT USE CASE EXAMPLES

## 2.3 THE FUNCTIONALITIES

The Energy Transformation tool can be used in two modes:

- **Analysis mode**: knowing the technology and its main components (either user-defined or default ones), the tool gives a component list with all the attributes needed for the assessment tools (performance, reliability, environmental and cost.
- **Design mode**: the tool gives the same type of outputs as the previous mode, but the results can be compared for different characteristic dimensions for the three transformation levels (mechanical transformation, electrical transformation, grid conditioning).

At the same time, three different complexity levels (i.e. early, mid, late stage) can be selected for the three Energy Transformation objects (i.e. mechanical transformation, electrical transformation, grid conditioning). At complexity level 1 (early level), simplified models have been considered. At complexity level 2 (mid stage), advanced models have been developed to obtain efficiency (linearized models to be computed in frequency domain) and reliability (critical failure models have been designed for each energy transformation step). Finally, at complexity level 3 (late stage), the user could add parameters for each transformation step definition.

Depending on the complexity levels selected for the objects, a global complexity level will be assigned considering the following parameters:

- Cmpx1: At least one of 3 parts has cmpx1
- Cmpx2: The three parts compx2
- Cmpx3: At least one of three has cmpx3
- Cmpx1 is not compatible with cmpx3

The Energy Transformation Module can design and assess four main sub-systems of the PTO:

- **Mechanical Transformation**: Designs the mechanical parts and performs the calculation of the PTO mechanical efficiency and loads knowing:
  - The PTO technology from the User
  - The resource from the Site Characterisation module
  - The absorbed energy and the device motion from the Energy Capture tool
  - The control strategy (passive control or user defined)
  - The component database
- **Electrical Transformation**: Designs the electrical parts and computes the generator efficiency and loadings knowing the mechanical PTO power and operation range.
- **Grid Conditioning**: Designs the components for grid conditioning electrical power, mainly selects the power converter, computes its efficiency, and the electrical output power.
- **Control Strategy** is dedicated to traducing device motions and loadings to specific velocity distributions to be accounted for in the conversion chain.

The ET module uses the following global metrics to drive PTO design:

- Array Annual Transformed Energy (AATE) to Total PTO array Cost [kWh/€]:

$$Cost_{Ratio} = \frac{AATE\ [kWh]}{PTO_{Cost}[€]}$$

- Array Annual Transformed Energy to Total PTO array Damage [kWh·yr]

$$Reliability_{Ratio} = \frac{AATE\ [kWh]}{Damage[1/yr]}$$

Finally, the ET module outputs provide information about cost, efficiency, reliability and mass of the different energy transformation objects.

In Table 2-2, there is a summary of the functionalities depending on the levels of complexity and the type of technology.

TABLE 2-2: FUNCTIONALITY CASES OF ENERGY TRANSFORMATION

| Functionalities | Level of complexity | Wave/Tidal | Total Cases |
|---|---|---|---|
| Create Array/Devices/PTOs | 3 | 2 | 6 |
| Performance assessment (Energy Transformation & Failure Rates on all PTOs) | 3 | 2 | 6 |
| Aggregated Transformed Power/Energy in the three stages at device and array levels | 3 | 2 | 6 |
| Bill of Materials and Hierarchy variables building – Array Level | 1 | 2 | 2 |
| **TOTAL** | | | **20** |

# 3. THE IMPLEMENTATION

## 3.1 THE ARCHITECTURE OF THE TOOL

The following UML diagram shows an overview of the Energy Transformation module displaying the flow of actions when running the design tool. All functionalities of the module are based on the lowest level objects, as specified in Figure 3.1, namely the 'Control Strategy', 'Mechanical Transformation', 'Electrical Transformation' and 'Grid Conditioning' objects.

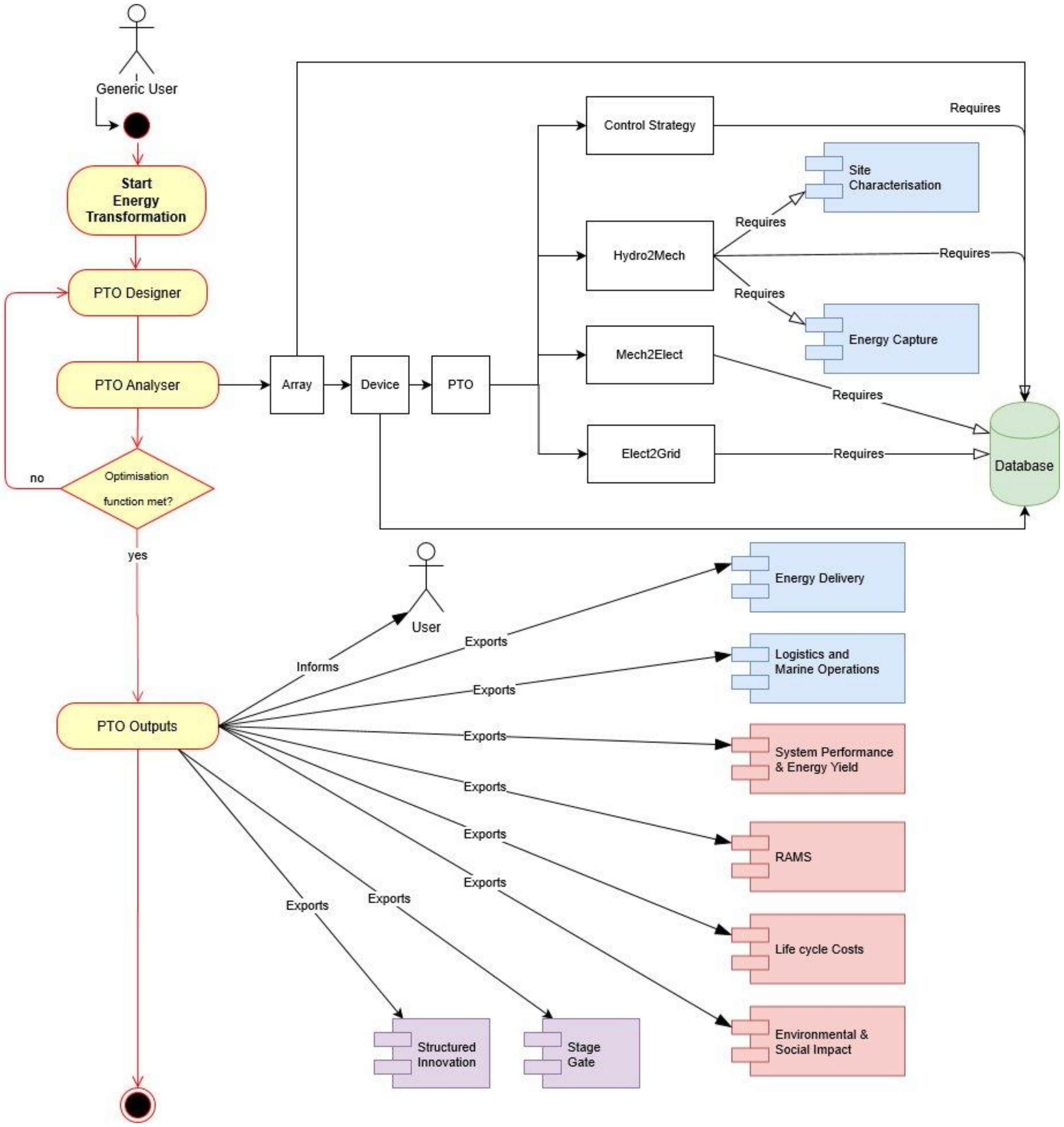


FIGURE 3.1: GENERAL ARCHITECTURE OF THE ENERGY TRANSFORMATION MODULE.

The 'PTO Analyser' object specified in Figure 3.1 represents the whole array from the Energy Transformation perspective. Therefore, it represents all PTOs within a device, as seen in Figure 3.2., and all devices within an array, as shown in Figure 3.3.

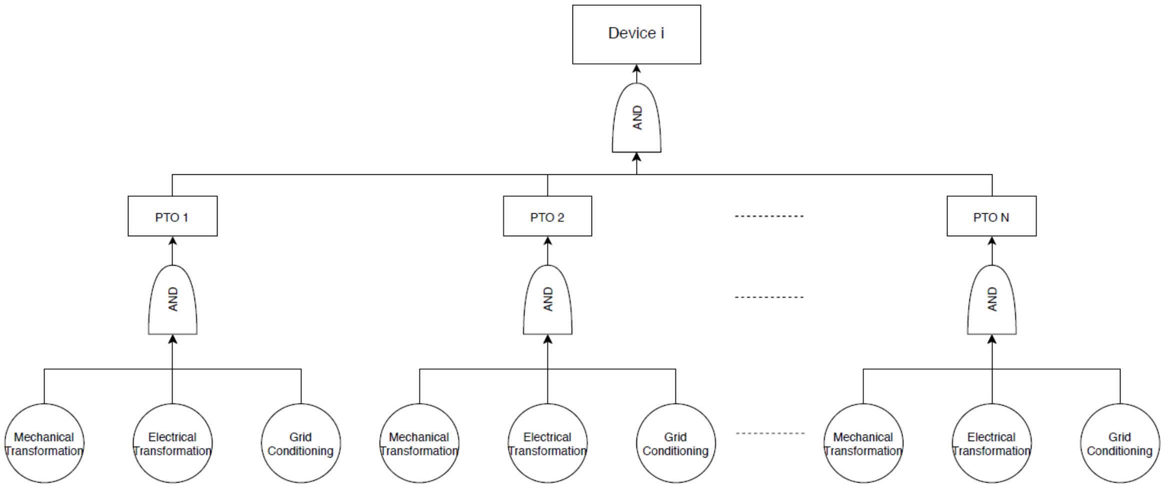


FIGURE 3.2. DEVICE HIERARCHY IN THE ENERGY TRANSFORMATION MODULE

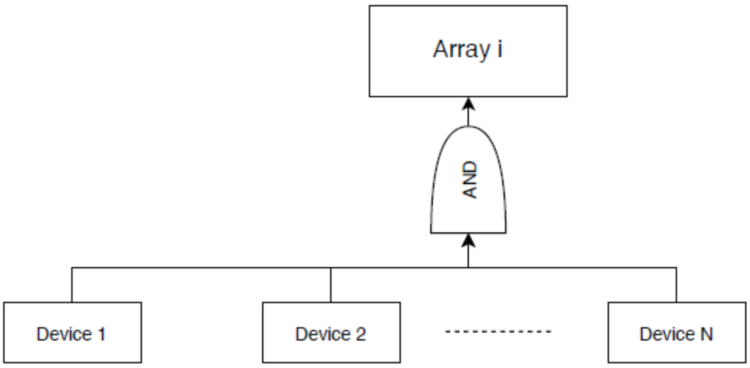


FIGURE 3.3: ARRAY HIERARCHY IN THE ENERGY TRANSFORMATION MODULE

One of the main functionalities of the ET module is to design the PTOs of the devices within a defined array, represented by the 'PTO Designer' object in Figure 3.1. In order to carry out such designs, several arrays can be computed performing sensitivity analyses so that the design provided is based on the best performance of module's specific metrics. In the Energy Transformation module, two metrics are assessed, the Array Annual Transformed Energy to Total PTO array Cost [kWh/€] and the Array Annual Transformed Energy to Total PTO array Damage [kWh·yr].

Finally, the module sends a series of outputs to two Deployment tools and the four Assessment tools:

- Deployment tools consuming from ET:
  - Energy Delivery (ED)

  - Logistics and Marine operations (LMO)
- Assessment tools consuming from ET:
  - System performance and energy yield (SPEY)
  - Lifecycle costs assessment (LCA)
  - Reliability-Availability-Maintainability-Survivability (RAMS)
  - Environmental and social impacts assessment (ESA)

Additionally, the Structured Innovation (SI) and Stage Gate (SG) tools also consume the module outputs in order to provide areas with innovation potential as well as the estimated stage of technology development, respectively.

## 3.2 BUSINESS LOGIC

The business logic is made up of 8 main objects which depend on one another as specified in the hierarchy Figure 3.2 and Figure 3.3, including:

- Mechanical Transformation
- Electrical Transformation
- Grid Conditioning
- Control
- PTO
- Device
- Array
- ET_Design

All objects are subsequently described in a top-down order.

### 3.2.1 ET_Design

It is the highest-level object of the module. Its main function is to store all Array objects developed within a project along with the two module internal metrics that enable local (i.e. ET Module) optimization.

INPUTS:

- ET_id: It is the identifier (primary key provided by the database)
- ET_name: It is the 'human readable' identifier.

OUTPUTS:

- Annual Transformed Energy (AATE) to Total PTO array Cost [kWh/€]:

$$Cost_{Ratio} = \frac{AATE\ [kWh]}{PTO_{Cost}[€]}$$

- Array Annual Transformed Energy to Total PTO array Damage [kWh·yr]:

$$Reliability_{Ratio} = \frac{AATE\ [kWh]}{Damage[1/yr]}$$

- Array object

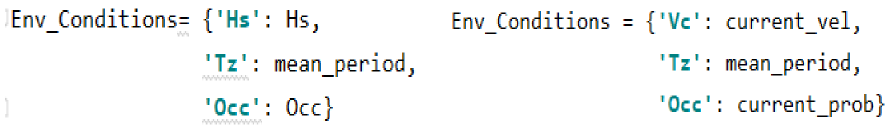
### 3.2.2 Array

Array objects have been created in order to store the performance of all devices within it, representing in the most realistic way all aggregated information at array level needed by the consumer modules, e.g. mean power, energy, cost, mass.

INPUTS:

- Array_ID: This a database generated identifier for the array object
- Array_name: Human readable array identifier
- Array inputs: Generic information at array level
  - Technology: Whether it is wave or tidal
  - Number of devices
- Complexity Level: This variable defines the complexity level of the array, that depends on the models used in the lowest level objects (Mechanical Transformation, Electrical Transformation and Grid Conditioning). As shown in sections 3.2.5 to 3.2.7, each transformation stage can be carried out with a 'Simplified' object, a 'Realistic' object or a 'Realistic-User_Defined' object. Each stage is related to complexity 1, 2 and 3 respectively. Since there are three transformation stages, multiple combinations arise, however, the next is assumed:
  - Complexity Level 1: At least one transformation is carried out with the corresponding 'Simplified' object and none of them can be 'Realistic-User_Defined'
  - Complexity Level 2: The three transformation stages must be carried out with 'Realistic' objects.
  - Complexity Level 3: At least one transformation is carried out with the corresponding 'Realistic-User_Defined' object and none of them can be 'Simplified'.
- Device Inputs: Information related to the configuration of the devices making up the array, utilised to initialise all devices. It is a dictionary defining one device and the initialisation of the array assumes all devices within the array are exactly equal. This input variable is specified in detail in section 3.2.3.
- PTO_inputs: Information related to the configuration of the PTOs making up the corresponding device, utilised to initialise all PTOs. It is a list of four dictionaries defining each of the three transformation objects as well as the control one. This input variable is specified in detail in section 3.2.4
- Array_performance_inputs: This variable is a list of dictionaries with as many elements as devices in the array, representing the captured power of each of them along with the corresponding force/speed. Each position of this list is detailed in section 3.2.3.
- Environmental Conditions: It is a dictionary representing the environmental conditions the array is subjected to. It is made up of three fields, different depending on the technology as illustrated in

Figure 3.4. Each field is a list defining the number of environmental conditions the array is subjected to. The outputs at array level are reset for each set of environmental conditions. Therefore, if the same array is analysed with different sets of environmental conditions, intermediate savings in the database must be performed and will be treated as independent arrays in terms of storage.



```
Env_Conditions= {'Hs': Hs,
                 'Tz': mean_period,
                 'Occ': Occ}
```

```
Env_Conditions = {'Vc': current_vel,
                  'Tz': mean_period,
                  'Occ': current_prob}
```

FIGURE 3.4: ENVIRONMENTAL CONDITIONS FIELDS FOR WAVE (LEFT) AND TIDAL (RIGHT)

OUTPUTS:

- Bill of Materials: It summarizes the objects used for the transformation, the corresponding catalogue position as well as its unit and total cost. An example is illustrated in Table 3-1.

TABLE 3-1: BILL OF MATERIALS EXAMPLE FOR A WAVE CASE AND COMPLEXITY LEVEL 2 ARRAY

| Design id | Id_catalogue | Size | Component name | Units | Unit costs [€] | Total cost [€] |
|---|---|---|---|---|---|---|
| ET_01 | H2M_01 | 1.2 | Airturbine | 6 | 2000 | 12000 |
| ET_01 | M2E_01 | 1.00E+05 | SCIG | 6 | 2000 | 12000 |
| ET_01 | E2G_01 | 1.00E+05 | B2B | 6 | 2000 | 12000 |

- Hierarchy: It collects all objects within an array setting the relations between components. Such relations establish to which device belongs each PTO and to which array belongs each device. Additionally, the failure rate of the lowest level objects is provided (Mechanical Transformation, Electrical Transformation and Grid Conditioning) based on the corresponding reliability models specified in 3.2.5 to 3.2.7. Also, the Shutdown flag is collected from the GUI so that LMO can take it into consideration to design the maintenance strategies. The Shutdown flag indicates the minimum number of PTOs to have the device ON (i.e. in operation) out of the total PTOs within it. An example of hierarchy is demonstrated in Table 3-2.

**TABLE 3-2: HIERARCHY EXAMPLE FOR AN ARRAY WITH 3 DEVICES, EACH DEVICE WITH 2 PTOS AND EACH PTO WITH THE 3 CORRESPONDING TRANSFORMATION STAGES**

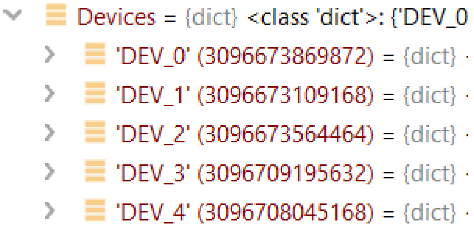
| System | Name of node | Design ID | Type | Category | Parent | Child | Gate Type | Failure rate [1/year] |
|---|---|---|---|---|---|---|---|---|
| ET | DEV_1 | ET_01 | System | Level 2 | N/A | [PTO_1_1. PTO_1_2] | K/N | N/A |
| ET | DEV_2 | ET_01 | System | Level 2 | N/A | [PTO_2_1. PTO_2_2] | K/N | N/A |
| ET | DEV_03 | ET_01 | System | Level 2 | N/A | [PTO_3_1. PTO_3_2] | K/N | N/A |
| ET | PTO_1_1 | ET_01 | PTO | Level 1 | ET_1 | [MechT_1_1, ElectT_1_1, GridC_1_1] | AND | N/A |
| ET | PTO_1_2 | ET_01 | PTO | Level 1 | ET_1 | [MechT_1_2, ElectT_1_2, GridC_1_2] | AND | N/A |
| ET | PTO_2_1 | ET_01 | PTO | Level 1 | ET_2 | [MechT_2_1, ElectT_2_1, GridC_2_1] | AND | N/A |
| ET | PTO_2_2 | ET_01 | PTO | Level 1 | ET_2 | [MechT_2_2, ElectT_2_2, GridC_2_2] | AND | N/A |
| ET | PTO_3_1 | ET_01 | PTO | Level 1 | ET_3 | [MechT_3_1, ElectT_3_1, GridC_1_1] | AND | N/A |
| ET | PTO_3_3 | ET_01 | PTO | Level 1 | ET_3 | [MechT_3_2, ElectT_3_2, GridC_3_2] | AND | N/A |
| ET | MechT_1_1 | ET_01 | Component | Level 0 | PTO_1_1 | N/A | N/A | value |
| ET | MechT_1_2 | ET_01 | Component | Level 0 | PTO_1_2 | N/A | N/A | Value |
| ET | MechT_2_1 | ET_01 | Component | Level 0 | PTO_2_1 | N/A | N/A | Value |
| ET | MechT_2_2 | ET_01 | Component | Level 0 | PTO_2_2 | N/A | N/A | Value |
| ET | MechT_3_1 | ET_01 | Component | Level 0 | PTO_3_1 | N/A | N/A | Value |
| ET | MechT_3_2 | ET_01 | Component | Level 0 | PTO_3_2 | N/A | N/A | Value |
| ET | ElectT_1_1 | ET_01 | Component | Level 0 | PTO_1_1 | N/A | N/A | Value |
| ET | ElectT_1_2 | ET_01 | Component | Level 0 | PTO_1_2 | N/A | N/A | Value |
| ET | ElectT_2_1 | ET_01 | Component | Level 0 | PTO_2_1 | N/A | N/A | Value |
| ET | ElectT_2_2 | ET_01 | Component | Level 0 | PTO_2_2 | N/A | N/A | Value |
| ET | ElectT_3_1 | ET_01 | Component | Level 0 | PTO_3_1 | N/A | N/A | Value |
| ET | ElectT_2_2 | ET_01 | Component | Level 0 | PTO_3_2 | N/A | N/A | Value |
| ET | GridC_1_1 | ET_01 | Component | Level 0 | PTO_1_1 | N/A | N/A | Value |
| ET | GridC_1_2 | ET_01 | Component | Level 0 | PTO_1_2 | N/A | N/A | Value |
| ET | GridC_2_1 | ET_01 | Component | Level 0 | PTO_2_1 | N/A | N/A | Value |
| ET | GridC_2_2 | ET_01 | Component | Level 0 | PTO_2_2 | N/A | N/A | Value |
| ET | GridC_3_1 | ET_01 | Component | Level 0 | PTO_3_1 | N/A | N/A | Value |
| ET | GridC_3_2 | ET_01 | Component | Level 0 | PTO_3_2 | N/A | N/A | value |

- Array Cost: It is the total cost of all PTOs and devices within the array. Its value corresponds with the sum of the last column of the Bill of Materials, Figure 3.5.
- Array Mass: This variable is broken down into the main materials of the transformation stages. Since each transformation stage is assigned with a main material, it is broken down into three fields, e.g. copper, aluminium, steel. And the total array mass of each material is provided.
- Array Annual Mean Mechanical Power: A list of the mean Mechanical power (after the Mechanical Transformation) with as many positions as environmental conditions the array is subject to. It corresponds with the Power Matrix and the Power curve, for wave and tidal cases respectively, of the mechanical power on the shaft connecting the Mechanical Transformation and Electrical Transformation objects.
- Array Annual Mean Electrical Power: A list of the mean Electrical power (after the Electrical Transformation) with as many positions as environmental conditions the array is subject to. It corresponds with the Power Matrix and the Power curve, for wave and tidal cases respectively, of the electrical power on the cables connecting the Electrical Transformation and the Grid Conditioning object.
- Array Annual Mean Grid Conditioned active/reactive Power: these are provided as two separate variables for the active and reactive power. Each of the variables is a list of the mean Active/Reactive Grid Conditioned power (after the Grid Conditioning) with as many positions as environmental conditions the array is subject to. It corresponds with the Power Matrix and the Power curve, for wave and tidal cases respectively, and the Grid Conditioned active/reactive power on the cable interfacing the device with the Energy Delivery module.
- Array Annual Transformed Mechanical/Electrical/Grid Conditioned (Active) Energy: These are the transformed energy aggregated at array level after each transformation stage. It is computed as described in the following equation:

$$E_{M/E/G\ array} = 24 \cdot 365 \cdot \sum_{n=1}^{EC\ number} \bar{P}_{M/E/G\ array_n} \cdot Occ_n$$

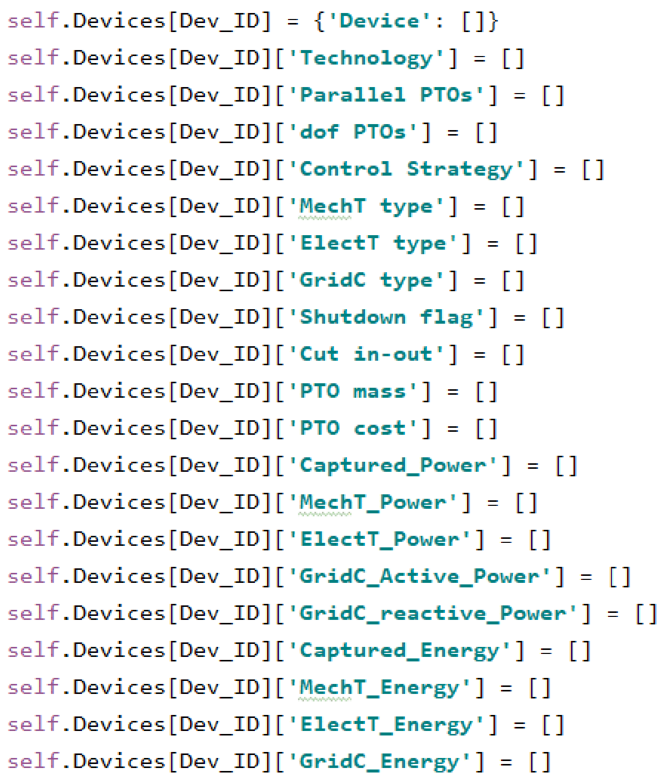
OBJECT METHODS:

- __init__: This method is run when the object is created out of the Array class. It initialises the Array. To do so, all Array inputs are stored in the corresponding variables and all output variables are initialised specifying the required dimensions and fields of the dictionaries. In addition to the inputs and outputs a variable called 'Devices' is initialised, belonging to the Array object. The 'Devices' variable is a list with as many positions as the devices within the array. Each position will contain the corresponding device object and the dictionary with all outputs at Device level, that will be specified in section 3.2.3. Figure 3.5 and Figure 3.6 show an example of array object and the variables of device object.



```
Devices = {dict} <class 'dict'>: {'DEV_0
    'DEV_0' (3096673869872) = {dict} ·
    'DEV_1' (3096673109168) = {dict} ·
    'DEV_2' (3096673564464) = {dict} ·
    'DEV_3' (3096709195632) = {dict} ·
    'DEV_4' (3096708045168) = {dict} ·
```

**FIGURE 3.5: EXAMPLE OF AN ARRAY OBJECT WITH FIVE DEVICES**



```
self.Devices[Dev_ID] = {'Device': []}
self.Devices[Dev_ID]['Technology'] = []
self.Devices[Dev_ID]['Parallel PTOs'] = []
self.Devices[Dev_ID]['dof PTOs'] = []
self.Devices[Dev_ID]['Control Strategy'] = []
self.Devices[Dev_ID]['MechT type'] = []
self.Devices[Dev_ID]['ElectT type'] = []
self.Devices[Dev_ID]['GridC type'] = []
self.Devices[Dev_ID]['Shutdown flag'] = []
self.Devices[Dev_ID]['Cut in-out'] = []
self.Devices[Dev_ID]['PTO mass'] = []
self.Devices[Dev_ID]['PTO cost'] = []
self.Devices[Dev_ID]['Captured_Power'] = []
self.Devices[Dev_ID]['MechT_Power'] = []
self.Devices[Dev_ID]['ElectT_Power'] = []
self.Devices[Dev_ID]['GridC_Active_Power'] = []
self.Devices[Dev_ID]['GridC_reactive_Power'] = []
self.Devices[Dev_ID]['Captured_Energy'] = []
self.Devices[Dev_ID]['MechT_Energy'] = []
self.Devices[Dev_ID]['ElectT_Energy'] = []
self.Devices[Dev_ID]['GridC_Energy'] = []
```

**FIGURE 3.6:EXAMPLE OF FIELDS IN A VARIABLE DEVICE CREATED AND FILLED IN THE ARRAY OBJECT**

- Performance: This function executes all devices in the array, created in the __init__ function, subject to the Environmental Conditions input. To run the Array_performance_inputs list is needed as each device is assumed to be able to capture a different amount of energy. Doing that, the performance data of each device is stored in the corresponding device object and the power and energy is aggregated to be provided at array level. The corresponding failure rate of each transformation stage of all PTOs is also stored in the hierarchy.

### 3.2.3 Device

Device objects are built as composed of a number of PTOs in order to provide all transformed power, energy, cost and mass at device level. It is the most relevant object in the business logic since it takes all the environmental conditions passed by its Array object and assesses all PTOs of the device, depending on whether the device is a Wave or Tidal device.

INPUTS:

- Device_ID: This a database generated identifier for the device object
- Device_name: Human readable device identifier
- Device inputs: Generic information at device level. It is a dictionary with all the required fields that makes a device from the ET perspective, described here:

  - dof_PTO: These are the number of device -mostly relative- motions used to generate power, e.g. a Pelamis device with three hinges would have a dof_PTO=2 or an Orbital device with two turbines would have a dof_PTO=2.
  - Parallel_PTOs: This represents the number of PTOs set in parallel to extract energy from each dof_PTO, e.g. in each Pelamis hinge two independent PTO sets (MechT, ElectT and GridC) working in parallel would have a Parallel_PTO=2 or in a MARMOK type device (one chamber→dof_PTO=1) with two air turbines would have a Parallel_PTO=2.
  - Shutdown_flag: As already introduced in the hierarchy ( section 3.2.1 ), this a device level variable, an indicates the minimum number of PTOs to have the device ON out of the total PTOs within it.
  - Cut in / cut out: It is a list with two positions indicating the minimum and maximum Hs/Vc (depending on whether it is a wave or a tidal case) that defines the range within which the device is assumed to generate power.
- Device Performance Inputs: It is a dictionary with the required fields to specify the captured power by the device that is gathered from Machine Characterization (MC) and Energy Capture modules (EC). It consists of the following fields depending on the device technology:
  - Wave devices:
    - Sigma_v: It represents the standard deviation of the velocity of the device in which the PTO acts
    - Cpto: It is the PTO damping applied in the corresponding degree of freedom and sea state
    - These fields assume that the system is linear (or linearized) and that PTO damping is not changed within the sea state. Therefore, the power and PTO force are computed as specified in equations below:

$$(1)\ \bar{P} = C_{pto} \cdot \int_0^\infty |H_v(\omega)|^2 \cdot S_\eta(\omega) \cdot d\omega = C_{pto} \cdot {\sigma_v}^2$$

$$(2)\ F_{pto}(t) = C_{pto} \cdot v(t)$$

  - Tidal devices:
    - $\sigma_V$: It represents the standard deviation of the current speed for a given mean current speed
    - Cpto: It is the factor that multiplied by the square of the current speed provides the captured power
    - $C_{t\_tidal}$: Is the inverse of the mean rotational speed of the turbine rotor
    - V: spped of the device
    - $V_{curr}$ : Current speed

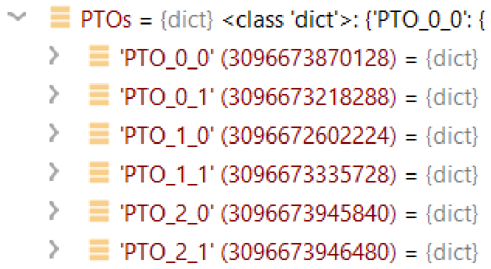
$$(3)\ P(t) = C_{pto} \cdot V_{curr}(t)^2 = \bar{V}_{curr} \cdot \frac{1}{2} \cdot C_p \cdot \rho_{water} \cdot \pi \cdot R^2 \cdot V_{curr}(t)^2$$

$$(4)\ F_{pto}(t) = C_{t\_tidal} \cdot C_{pto} \cdot V_{curr}(t)^2$$

    - It should be noted that the presented equation (3) of power for tidal devices is not exactly proportional to the cubic of the current speed but to the square times the mean current speed. In order to provide theoretical probability density functions of the power, it has been assumed that the rotational speed of the rotor is constant per mean current speed, and therefore the power turns out as the provided expression.
- Environmental Conditions: The environmental conditions are provided exactly as provided at array level. However, in the tidal case, each mean speed must be modified accounting for the current speed field as provided by the Energy Capture module

OBJECT METHODS:

- __init__: This method is run when the object is created out of the Device class. It initialises the Device, and it is called from within the array __init__ method. To do so, all device inputs are stored in the corresponding variables and all output variables are initialised specifying the required dimensions and fields of the dictionaries. In addition to the inputs and outputs a variable called 'PTOs' is initialised, belonging to the Device object. The 'PTOs' variable is a list with as many positions as PTOs (dof_PTO·Parallel_PTO) within the device. Each position will contain the corresponding PTO object and the dictionary with all outputs at PTO level, that will be specified in section 3.2.4. Figure 3.7 represents an example of PTOs variable in a device object and Figure 3.8 an example of Fields in a PTO in PTOs variable. Created and filled in the Device object



```
PTOs = {dict} <class 'dict'>: {'PTO_0_0': {
    'PTO_0_0' (3096673870128) = {dict}
    'PTO_0_1' (3096673218288) = {dict}
    'PTO_1_0' (3096672602224) = {dict}
    'PTO_1_1' (3096673335728) = {dict}
    'PTO_2_0' (3096673945840) = {dict}
    'PTO_2_1' (3096673946480) = {dict}
```

FIGURE 3.7: EXAMPLE OF A DEVICE WITH SIX PTOS (3 DOF_PTOS AND 2 PARALLEL_PTOS)

```
self.PTOs[PTO_ID]={'PTO': []}
self.PTOs[PTO_ID]['Mech_size'] = []
self.PTOs[PTO_ID]['Mech_mass'] = []
self.PTOs[PTO_ID]['Mech_cost'] = []
self.PTOs[PTO_ID]['Elect_P_rated'] = []
self.PTOs[PTO_ID]['Elect_mass'] = []
self.PTOs[PTO_ID]['Elect_cost'] = []
self.PTOs[PTO_ID]['Grid_P_rated'] = []
self.PTOs[PTO_ID]['Grid_mass'] = []
self.PTOs[PTO_ID]['Grid_cost'] = []
self.PTOs[PTO_ID]['MechT_Damage'] = []
self.PTOs[PTO_ID]['ElectT_Damage'] = []
self.PTOs[PTO_ID]['GridC_Damage'] = []
self.PTOs[PTO_ID]['Captured_Power'] = []
self.PTOs[PTO_ID]['MechT_Power'] = []
self.PTOs[PTO_ID]['ElectT_Power'] = []
self.PTOs[PTO_ID]['GridC_Active_Power'] = []
self.PTOs[PTO_ID]['GridC_reactive_Power'] = []
self.PTOs[PTO_ID]['Captured_Energy'] = []
self.PTOs[PTO_ID]['MechT_Energy'] = []
self.PTOs[PTO_ID]['ElectT_Energy'] = []
self.PTOs[PTO_ID]['GridC_Energy'] = []
```

FIGURE 3.8: EXAMPLE OF FIELDS IN A PTOS VARIABLE CREATED AND FILLED IN THE DEVICE OBJECT

### 3.2.4 PTO

The business logic can be used in three modes, early stage (cmpx1), middle stage (cmpx2) and late stage (cmpx3) for the different energy transformation steps and the 9 options are compatible one another.

Regarding simplified models, the reliability model has been done in the same way for the three transformation levels: A fatigue curve has been developed considering that if the element works at the 50% of each capacity one year, the device will need a maintenance in one year. And if the device works 10 times at the capacity the device durability will be the 10% of the annual cycles. This refers to the cost of the device (based on internal knowledge and consults with suppliers): 500€, 100€ and 100€ per dimension and nominal power has been considered and referring to the weight 120kg, 10kg and 10kg per kW installed.

The module has been developed considering three different objects, PTO level, Device Level and Array level. At the main threat the array level object is initialized and respectively inside object device and the PTO.

### 3.2.5 Mechanical transformation

For this module, the design of the hydrodynamic to mechanic transformation is completed, through calculation of the PTO mechanical efficiency, loads estimation (reliability), weight and cost estimation. For this issue is necessary to have the following information:

- The PTO technology from the User
- The resource from the Site Characterization module
- The absorbed energy and the device motion from the Energy Capture tool
- The control strategy
- The component database

Regarding PTO technologies, three different types have been implemented:

- Air turbine (wave) (Section 3.2.5.1)
  - Wells turbine
  - Biradial turbine
- Hydraulic (wave) (Section 3.2.5.2)
- Gearbox (wave/tidal) (Section 0)

#### 3.2.5.1 Air turbines

Figure 3.9 shows the two types of self-rectifying air turbines that have been considered here. The traditional Wells turbine [4] and the biradial turbine [5]

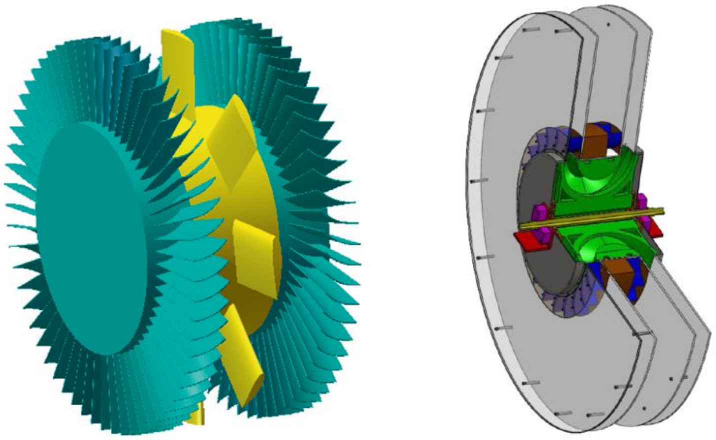


FIGURE 3.9: WELLS TURBINE (LEFT) AND THE BIRADIAL TURBINE (RIGHT) [4] , [5]

### 3.2.5.1.1 Performance

The non-dimensional performance properties of both turbines have been stored in the DTOceanPlus database. The performance is dimensionalized with the diameter of the turbine and the working rotational speed.Figure 3.10 represents the non-dimensional air flow with the pressure for biradial and wells turbines:

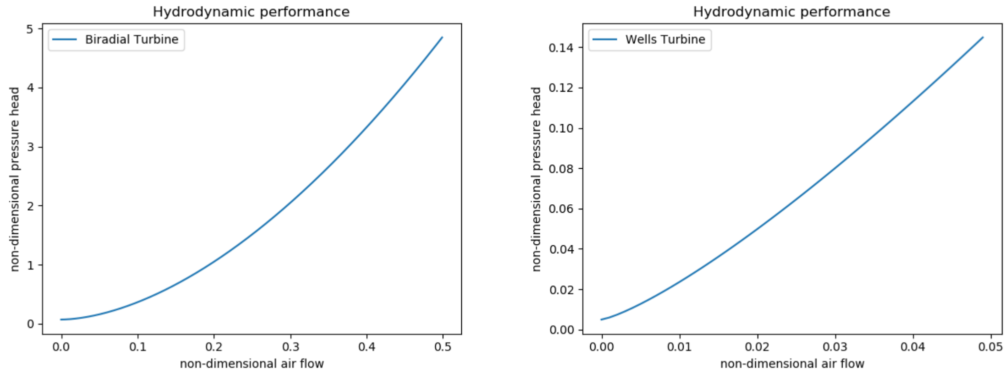


FIGURE 3.10: HYDRODYNAMIC NON-DIMENSIONAL PROPERTIES OF THE BIRADIAL AND WELLS TURBINES

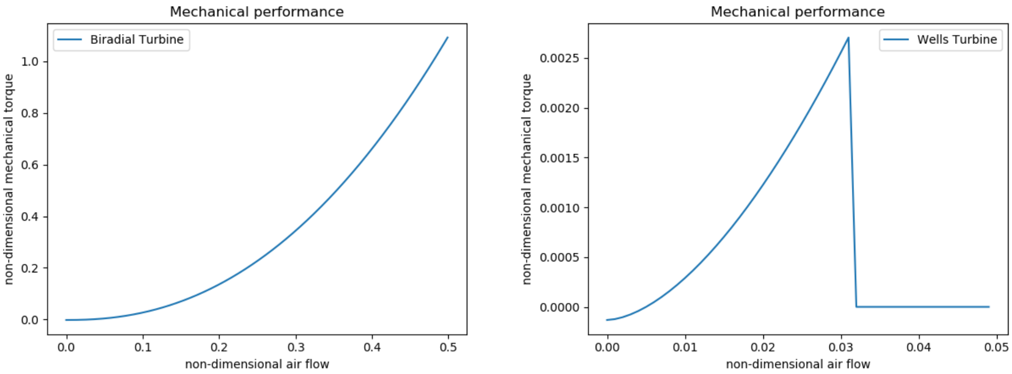


FIGURE 3.11: MECHANICAL NON-DIMENSIONAL PROPERTIES OF THE BIRADIAL AND WELLS TURBINES

Turbine dimensional hydrodynamic and mechanical performance is based on equations (5):

$$(5)\ \Psi = \frac{P}{\rho \cdot \omega^2 \cdot D^2} \quad \Pi = \frac{T}{\rho \cdot \omega^2 \cdot D^5} \quad \Phi = \frac{S \cdot V}{\omega \cdot D^3}$$

Reference data have been gathered from [5] and [6], and it is approximated at the object initialization step with a function of the form:

$$(6)\ \Psi = K_p \cdot \Phi^{\alpha_p} + K_{p0} \qquad \Pi = K_t \cdot \Phi^{\alpha_t} + K_{t0}$$

It applies both to the already included air turbines and to the user defined data at late stage.

Since the module works in the frequency domain, it is assumed that the rotational speed ω is kept constant per sea state. It enables linearization of the turbine with a linear function of the form $F_{pto} = C_{\text{pto}} \cdot \text{V}$ in an iterative manner so that it produces the same power of the equivalent non-linear function (6).Figure 3.12 shows non-dimensional pressure head of a wells turbine and the equivalent linearized turbine to capture the same amount of energy:

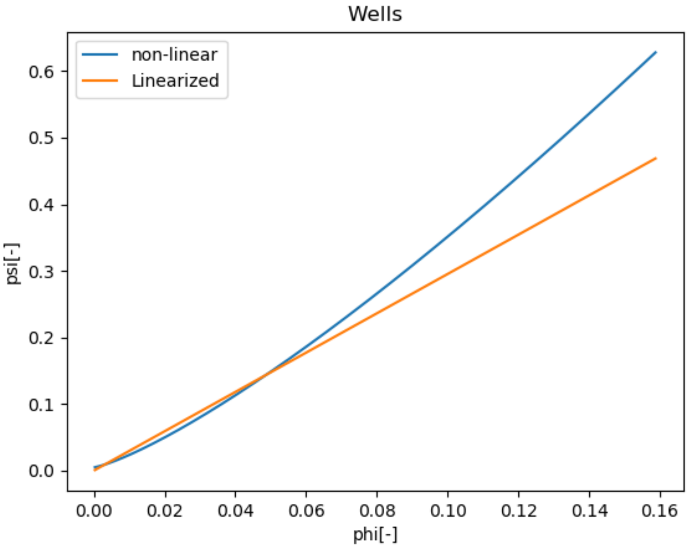


**FIGURE 3.12: NON-DIMENSIONAL PRESSURE HEAD OF A WELLS TURBINE AND THE EQUIVALENT LINEARIZED TURBINE TO CAPTURE THE SAME AMOUNT OF ENERGY**

The mechanical torque loss over non-dimensional flow of 0-0.03 represents the stall in the Wells turbine.

#### 3.2.5.1.2 Reliability

The reliability of the Air Turbines is based on the stress produced by torque on the shaft contained by the turbine itself for simplicity. The stress is assumed to be produced by the torsion torque, and hence it is a shear stress that is assessed.

$$(7)\ \tau_{shaft} = \frac{T \cdot D_{shaft}}{2 \cdot J_{shaft}}$$

Where T is the mechanical torque transmitted to the turbine shaft, D is the turbine shaft and J is the polar moment of inertia of the shaft. It is assumed that the shaft diameter corresponds, in the mid complexity mode, to a 10% the turbine rotor diameter.

The stress on the shaft is used to compute the corresponding strength in terms of number of cycles of the corresponding stress range through the recommended curves provided in [7].

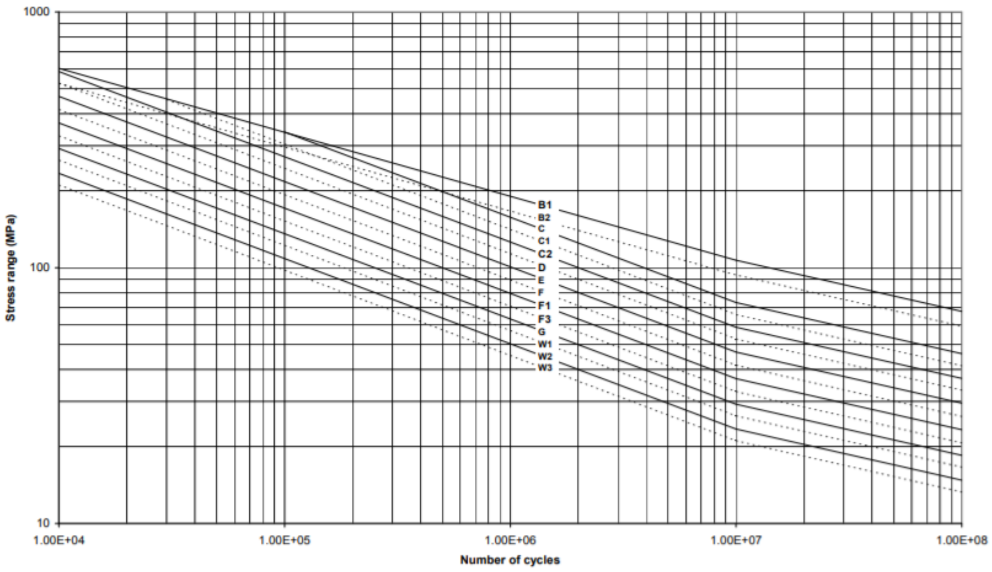


FIGURE 3.13: FATIGUE CURVES RECOMMENDED FOR COMPONENTS IN AIR [7].

All curves in Figure 3.15 are made up of two sections for a number of cycles lower and higher than $10^7$ respectively. Each section is defined by the following equation:

$$(8)\ log(N) = log(a) - m \cdot log(\Delta\sigma)$$

In order to be conservative, the considered curve for this component has been the W3 in Figure 3.13. The life obtained with the fatigue strength is afterwards used to compute the damage at each sea state or current velocity accounting for the probability attributed to each stress range.

#### 3.2.5.1.3 Cost assessment

The cost assessment of the Air Turbines has been defined through a cost function as suggested in [8]:

$$(9)\ C_{mech}(D) = C_{mech\,0}\left(\frac{D^3}{D_0^3}\right)^X$$

Where the reference values for equation (9) are $C_{mech\,0} = 330000\,€$ and $D_0 = 2.3m$ and the suggested exponent is $X = 2/3$.

The user has the option to modify the cost values at complexity level 3.

### 3.2.5.1.4 Environmental Impact

The environmental impact for the Air Turbines consists in calculating the total required mass of its main material. Therefore, the calculation is based on the total volume of the blades and the shaft, assuming both components are made up of the same material.

**Wells Turbine**

The Wells turbine is made up of a number of blades whose shape corresponds to the NACA_0015 profile, specified in [9]:

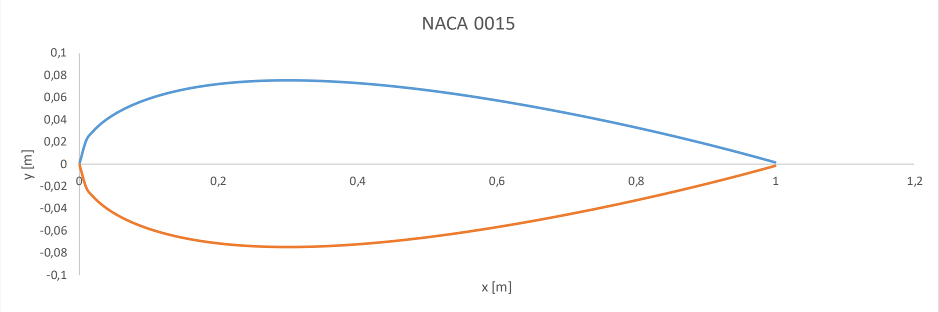


FIGURE 3.14: SHAPE OF THE SECTION OF THE NACA 0015

For the mass computation, the following parameters are assumed [6]:

- Number of blades: 8
- Inner to outer radius relation: 0.678
- Cross section area (chord=1): 0.1027[$m^2$]
- Chord to Diameter relation: 0.212
- Material density (steel): 7850[$m^3$]
- Shaft length=turbine diameter

**Biradial Turbine**

To estimate the total mass of the biradial turbine, the same approach has been considered, however, the volume of the blades is related to the turbine diameter through different parameters.

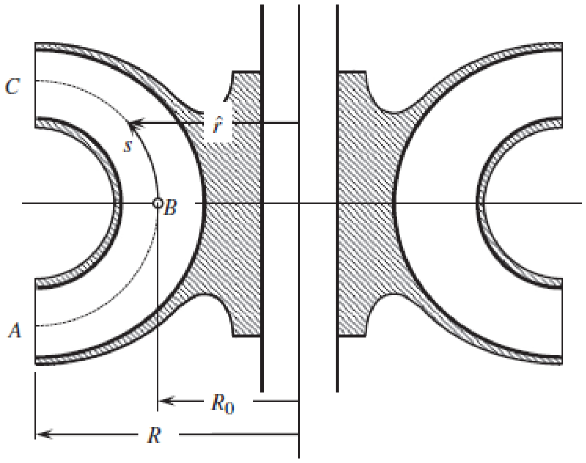


FIGURE 3.15: D PROJECTED BIRADIAL TURBINES BLADES [10]

The following parameters have been considered for the mass computation of the turbine [5]:

- Number of blades: 7
- Blade thickness to rotor radius: 0.015
- Blade length (s) to rotor radius: 0.45 (assuming s is projected in 2D for simplicity)
- Blade breadth to rotor radius: 0.22
- Material density (steel): 7850[$m^3$]
- Shaft length=turbine diameter

### 3.2.5.1.5 Catalogue

The definition of either specific Air Turbines or a set of them is assumed to be done through a user-defined data at the catalogue. The required fields are broken down into 3 categories as shown in table 3.1:

TABLE 3-3: CATALOGUE OF TURBINES

| Parameter | Description |
|---|---|
| **General information** | |
| ID | |
| Material | |
| Manufacturer | |
| Mass | |
| Cost | |
| **Constructive parameters** | |
| Type | |
| Diameter | |
| Shaft diameter | |
| **Performance and reliability parameters** | |
| Velocity | |

| Parameter | Description |
|---|---|
| Pressure drop | Defines the pneumatic side performance (P in equation (5)), |
| Torque | Mechanical side performance (T in equation (1)). |
| M1 | The variables m1, log(a1), m2 and log(a2) describe the fatigue curves as specified in 0. and equation (4). |
| Log(a1) | |
| m2 | |
| Log(a2) | |

### 3.2.5.2 Hydraulic Systems

A typical energy conversion system for energy converters, based on hydraulic power take-off (PTO) system, has been implemented throughout a linearization of equivalent force, consisting in a double-acting cylinder, a hydraulic motor and two or more accumulators. Figure 3.16 shows a typical configuration with 2 extra control accumulators [11].

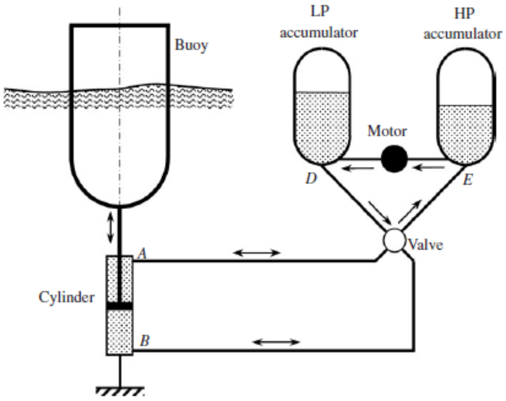


FIGURE 3.16: EXAMPLE OF A TYPICAL HYDRAULIC POWER TAKE OFF

When the device moves upwards, the pressure into the cylinder chamber $p_A$ and the pressure into the HP accumulator are both the same. Furthermore, the pressure $p_B$ is equal to the pressure in the LP accumulator. However, when the movement is downwards it is the pressure $p_B$ which takes the HP accumulator pressure value and $p_A$ the one of the LP accumulators. The valve prevents the fluid of going into the wrong accumulator.

The model has been linearized from the following typical equations that represent a hydraulic PTO [12]:

The motor pressure difference is modelled as used in this equation:

$$\Delta p_m = p_{HP} - p_{LP} = p_A - p_B - K \cdot \left(A_p \cdot \dot{x}\right)^2$$

if the displacement of the sphere is upwards. And with this equation if the movement is downwards:

$$\Delta p_m = p_{HP} - p_{LP} = p_B - p_A - K \cdot \left(A_p \cdot \dot{x}\right)^2$$

Where $K \cdot \left(A_p \cdot \dot{x}\right)^2$ represents the pressure losses through the system. $K$ is a coefficient of loss pressure due to friction along the circuit, $A_p$ is the cylinder area and $\dot{x}$ is the heave motion velocity.

To define the pressure value in the accumulators, an ideal gas and a polytropic process is assumed so it could be applied:

$$P_{gHP} = P_{0_{gHP}} \cdot \left(\frac{V_{0_{gHP}}}{V_{gHP}}\right)^{\gamma}$$
$$P_{gLP} = P_{0_{gLP}} \cdot \left(\frac{V_{0_{gLP}}}{V_{gLP}}\right)^{\gamma}$$

Where $P_{0_{gHP}}$, $P_{0_{gLP}}$, $V_{0_{gHP}}$ and $V_{0_{gLP}}$ are the initial conditions of gas pressure and gas volume inside the accumulators and $\gamma$ is the adiabatic index.

In order to calculate the pressure value in each accumulator, a previous operation is needed to find the gas volume:

$$V_{gHP} = V - V_{fHP}$$
$$V_{gLP} = V - V_{fLP}$$

$V$ is the volume of the accumulators and $V_{fHP}$, $V_{fLP}$ are the hydraulic fluid values inside each. To figure out these values, it is required to solve the next Ordinary Differential Equations (ODE):

$$\dot{V}_{fLP} = Q_m - A_p \cdot \dot{x}$$
$$\dot{V}_{fLP} = A_p \cdot \dot{x} - Q_m$$

Where:

| | |
|---|---|
| $\Delta p_m$ | difference of pressure at the accumulator |
| $p_A$ | Pressuro piston size A |
| $p_B$ | Pressure piston size B |
| K | Losses coefficient |
| $A_P$ | Piston area |
| $\dot{x}$ | Vertical speed |
| $p_B$ | Pressure accumulator B |
| $p_A$ | Pressure accumulator A |

| | |
|---|---|
| $V_{gHP}$ | Volume high pressure accumulator |
| $V_{gLP}$ | Volume low pressure accumulator |
| $Q_m$ | Flux at the motor |
| $\gamma$ | Isentropic parameter |

#### 3.2.5.2.1 Cost assessment and environmental impact

Next table represents the weight and cost for different dimensions considered on the catalogue hydraulic PTO (based on [13]):

**TABLE3-4: SUMMARY OF WEIGHT AND COST OF THE DIFFERENT ELEMENTS OF THE HYDRAULIC PTO COST AND WEIGHT BASED ON [13]**

| Nominal power per device (kW) | 20 | 50 | 100 | 200 | 500 | 1000 | UNITS |
|---|---|---|---|---|---|---|---|
| Vol. Acc princ | 93,66 | 234,15 | 468,29 | 936,59 | 2341,46 | 4682,93 | Liters |
| Weight Acc princ. | 330,73 | 826,83 | 1653,66 | 3307,32 | 8268,29 | 16536,59 | kg |
| Vol. Acc extra | 3,33 | 8,33 | 16,67 | 33,33 | 83,33 | 166,67 | Liters |
| Weight acc extra | 11,77 | 11,77 | 29,43 | 58,85 | 117,71 | 294,27 | kg |
| Vol. Acc reserva | 234,15 | 585,37 | 1170,73 | 2341,46 | 5853,66 | 11707,32 | Liters |
| Weight acc. Extra | 826,83 | 2067,07 | 4134,15 | 8268,29 | 20670,73 | 41341,46 | kg |
| Vol. Acc backup | 292,68 | 731,71 | 1463,41 | 2926,83 | 7317,07 | 14634,15 | Liters |
| Weight acc backup | 1033,54 | 2583,84 | 5167,68 | 10335,37 | 25838,41 | 51676,83 | kg |
| Hydraulic oil | 44,96 | 112,39 | 224,78 | 449,56 | 1123,90 | 2247,80 | Liters |
| Total Weight ACC | 2202,87 | 5489,51 | 10984,91 | 21969,83 | 54895,15 | 109849,15 | kg |
| Cost acc. Princp | 2873,44 | 7183,61 | 14367,22 | 28734,44 | 71836,10 | 143672,20 | € |
| Cost acc. Backup | 2244,88 | 5612,20 | 11224,39 | 22448,78 | 56121,95 | 112243,90 | € |
| Cost acc. Reserv. | 4109,85 | 10274,63 | 20549,27 | 41098,54 | 102746,34 | 205492,68 | € |
| Oil | 92,83 | 232,09 | 464,17 | 928,34 | 2320,86 | 4641,72 | € |
| Total liters | 668,78 | 1671,94 | 3343,89 | 6687,77 | 16719,43 | 33438,86 | Liters |
| Hydraulic motor | 708,00 | 1770,00 | 3540,00 | 7080,00 | 17700,00 | 35400,00 | € |
| Hydraulic motor weight | 60,00 | 150,00 | 300,00 | 600,00 | 1500,00 | 3000,00 | kg |
| TOTAL WEIGHT | 2262,87 | 5639,51 | 11284,91 | 22569,83 | 56395,15 | 112849,15 | kg |
| TOTAL COST | 10029,01 | 25072,52 | 50145,05 | 100290,10 | 250725,25 | 501450,50 | € |

#### 3.2.5.2.2 Reliability

For the reliability estimation, torsion torque stress on the shaft has been assumed.

$$(10)\ \tau_{shaft} = \frac{T \cdot D_{shaft}}{2 \cdot J_{shaft}}$$

Where T is the mechanical torque transmitted to the turbine shaft, D is the hydraulic motor diameter/ generator shaft and J is the polar moment of inertia of the shaft.

The stress on the shaft is used to compute the corresponding strength in terms of number of cycles of the corresponding stress range through the recommended curves provided in [7].

All curves in Figure 3.13 are made up of two sections for a number of cycles lower and higher than $10^7$ respectively. Each section is defined by the following equation:

$$\text{(11)}\quad log(N) = log(a) - m \cdot log(\Delta\sigma)$$

In order to be conservative, the considered curve for this component has been the W3. The life obtained with the fatigue strength is afterwards used to compute the damage at each sea state or current velocity accounting for the probability attributed to each stress range.

#### 3.2.5.2.3 Efficiency

For the efficiency estimation of the system has been obtained considering the volumetric efficiency and the torque efficiency [14]

$Q_m$ is the motor flow obtained from:

$$Q_m = \alpha \cdot D_\omega \cdot \omega \cdot K_q$$

$\alpha$ refers to the motor fractional displacement, $D_\omega$ is the motor displacement, $\omega$ is the motor angular velocity which to be obtained requires to solve another ODE and $K_q$ is the volumetric efficiency.

The equation to be solved to define the angular velocity is:

$$\dot{\omega} = \frac{T_m - T_{res}}{I}$$

$T_m$ represents the motor torque which formula is presented below, $T_{res}$ refers to a resistive torque and $I$ is the motor inertia.

$$T_m = \alpha \cdot D_\omega \cdot \Delta p_m \cdot K_t$$

Where $K_T$ is a torque efficiency.

Both efficiencies $(K_q, K_t)$ are obtained as follow from *Deliverable D3.1 Energy Storage Systems (SDWED)*:

$$K_q = \frac{1}{1 + \frac{C_s}{|\alpha| \cdot S} + \frac{\Delta p_m}{\beta} + \frac{C_{st}}{|\alpha| \cdot \sigma}}$$

$$K_t = 1 - \frac{C_v \cdot S}{|\alpha|} - \frac{C_f}{|\alpha|} - C_h \cdot \alpha^2 \cdot \sigma^2$$

Where:

Friction loss coefficients:

- $C_f$ is the friction coefficient
- $C_v$ is the viscous coefficient
- $C_h$ is the hydrodynamic coefficient

End Oil properties:

- $\beta$ is the oil bulk modulus
- $\mu$ is the oil viscosity
- $\rho$ is the oil density

Leakage coefficients:

- $C_s$ is the laminar flow coefficient
- $C_{st}$ is the turbulent flow coefficient

#### 3.2.5.2.4 Catalogue

Next table shows the catalogue for hydraulic PTO.

**TABLE 3-5: CATALOGUE FOR HYDRAULIC PTO**

| Parameter | Description |
|---|---|
| Cost | Parameter for cost estimation |
| Weight | Parameter for weight estimation |
| Eff _cf | Capacity factor normalized |
| Eff_eff | Efficiency per capacity factor |
| Reliab | |
| Fatigue life | W3 curve from DNV-RP-C203, two sections, limit 10**7 |
| Shaft diam | Diameter of the shaft |

### 3.2.5.3 Gearbox

Gearboxes are used to reduce speed and increase torque or reduce torque and increase speed between the PTO and the generator. They can be used in wave and tidal devices, although they are the most common mechanical transformation method for horizontal tidal turbines.

#### 3.2.5.3.1 Performance

Power loss in the gearbox is mostly due to friction, which generates heat. In miniature gearboxes, heat is not much of a problem because the power losses and the absolute amounts of power involved are relatively small. However, large gearboxes use oil coolers and pumps to compensate for gearbox inefficiency [15].

Thus, gearbox efficiency depends on friction. This in turn depends on the quality of the gearing, the number of tooth engagements (how many times one-wheel drives another) and the load torque (how much "moment" the gearbox has to deliver).

Most manufacturers will specify an intended gearbox operating point. Gearbox efficiencies in a spur gearbox at a 16-mm diameter vary from about 87% at a gear ratio of 6.3:1 to about 40% at a ratio of 10,683:1. A basic rule that designers use for spur gears is a 10% loss per engagement. One gear wheel in contact with another is defined as an engagement and the loss in that engagement is approximately 10%.

A general rule is **the lighter the load and the higher the ratio, the less likely it is that the gearbox will actually reach the manufacturers' specified efficiency**. Light loading and high ratios tend to produce poor gearbox efficiencies. But with heavy loading and high ratios, the gearbox will approach its theoretical efficiency.

In this simplified method, the following efficiency curve for 1 engagement spur gearbox has been considered as seen in Figure 3.20

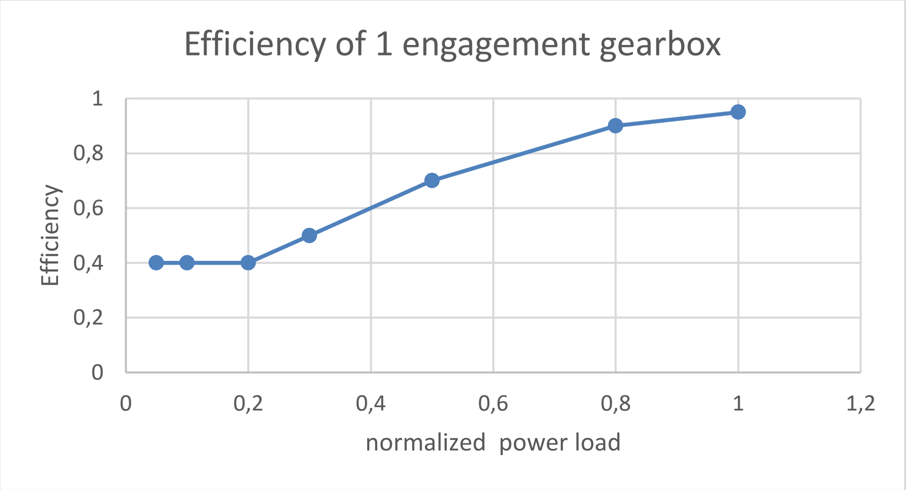


FIGURE 3.17: SPUR GEARBOX EFFICIENCY VS. POWER LOAD

Transmission relation is calculated as:

$$(12)\ i = \frac{\omega_2}{\omega_1}$$

As a design rule, transmission relation of a pair of wheels should remain within the range [1/8-8]. In this case, $w_2 > w_1$ so a maximum of $i = 8$ will be accepted. For higher transmission relations, a gear train must be used, more wheels.

The number of engagements will be:

$$(13)\ n_{eng} = \frac{i}{8} + 1$$

In this simplified calculation, if more than one engagement is used, the efficiency will reduce in 10% for each extra engagement.

### 3.2.5.3.2 Reliability

For calculating the reliability of a gearbox, the reliability of every critical component must be taken into account. In this case, the critical components are gears and bearings.

The life of a bearing is generally defined as the $L_{10}$ life, which is the duration after which 10% of the bearings will fail. If $L_{10}$ for one bearing is 20 years, then there is a 10% chance that the bearing will fail in less than 20 years.

**Bearing Rating Life Calculation**

"Rating life" is the bearing life calculated for 90% reliability. This is the amount of time that a group of apparently identical bearings will complete or exceed before the formation of a fatigue spall. The basic formula for calculating bearing $L_{10}$ rating life is (htt6):

$$(14)\ L_{10} = \frac{(C/P)^{e} 10^{6}}{60N}$$

where:

- $C$ = Dynamic Capacity (dN or Lbs). The load that bearing manufacturers specify will give one million revolutions of service. From bearings catalogue
- $P$ = Equivalent Bearing Load (N or Lbs) on a rotating radial bearing. Constant stationary radial load which, if applied to a bearing with a rotating inner ring and stationary outer ring, would give the same life as that which the bearing would attain under actual constant of variable conditions of load and rotation
- $N$ = Rotating speed in RPM
- $e$ = 3.0 for ball bearings, 10/3 for roller bearings

### 3.2.5.3.3 Equivalent Bearing Load

If a bearing is loaded with simultaneously acting radial load $\mathrm{Fr}$ and axial load $\mathrm{F}a$ that are constant in magnitude and direction, the equivalent dynamic bearing load P can be obtained from the general equation:

$$(15)\ P = X * Fr + Y * Fa$$

where

| | |
|---|---|
| P | equivalent dynamic bearing load [kN] |
| Fr | actual radial bearing load [kN] |
| Fa | actual axial bearing load [kN] |

X radial load factor for the bearing (from catalogue)

Y axial load factor for the bearing (From catalogue)

To calculate the loads, the following assumptions will be made:

- The gearbox can have one or several planetary stages, and one or several parallel stages. Each stage can rotate at different speeds and will have several bearings
- The shaft input torque is transmitted to the bearings and is distributed equally between the bearings of each stage

Calculation of the load of each stage:

The force acting on the gear is divided into radial load and axial load and their direction and ratio vary depending on the type of gear. In the case of the simplest flat gear direction of load is radial only and it is given by the following formula:

$$(16)\ Ft = 2000 * t/d$$

$$(17)\ Fr = Ft * tan\alpha$$

$$(18)\ Fc = \sqrt{F_t^2 + F_r^2}$$

Where:

$T$ : toque acting on the gear [Nm]

$d$ : pitch circle diameter of drive gear [mm]

$F_t$: force in tangent direction of gear [N]

$F_R$: force in radial direction of gear [N]

$F_c$: combine force acting perpendicular to gear [N]

Actual load to be used is the one resulting of

$$(19)\ F=Fc\cdot fz$$

Where $f_z$ is a gear factor that takes into account vibration and impact shock affecting the theoretical load obtained by the formula above.

TABLE 3-6: GEAR FACTOR Fz

| Type of gear | $f_z$ |
|---|---|
| Precision gear<br>(Both of pitch error and geometric error is 0,02 mm or less) | 1,05 -1 |
| Ordinary machined gear (Both of pitch error and geometric error is between 0,02 mm and 0,1 mm) | 1,1-1,3 |

Thus, for simplification purposes, for each gearbox stage bearings the Equivalent Load P will be calculated as:

$$(20)\ P = F/nof\ bearings\ of\ each\ stage$$

### Life Adjustment Factors

Life adjustment factors allow the original equipment manufacturer (OEM) to better predict the actual service lives and reliability of bearings that can be selected and installed at the equipment. An adjusted calculated $L_{10}$ rating life is calculated by using the following formula:

$$(21)\ L_{na} = a_1 a_{ISO} L_{10}$$

- $L_{na}$ = adjusted rating life
- $a_1$ = life adjustment factor for reliability
- $a_{ISO}$ = life adjustment factor for operating conditions, lubrication, cleanliness, etc.

Life adjustment factors, can theoretically be greater or less than 1.0, depending on their evaluation.

### Life Adjustment for Reliability - a1

In the OEM's process of predicting the service reliability of the equipment, it is sometimes necessary to increase the reliability of the selected bearings to predict a longer mean time between failures. The a1 factors shown in Table 3-7 are for increased values of reliability and come from tables [16] [17] . If a lower value for L10 is calculated with an a1 factor, and it is not acceptable, then a bearing with greater Dynamic Capacity needs to be chosen.

TABLE 3-7: THE A1 FACTORS FOR INCREASED VALUES OF RELIABILITY [16] [17] .

| Reliability - % Ln a1 factor |
|---|
| 90 L10 1.00 |
| 95 L5 0,64 |
| 96 L4 0,55 |
| 97 L6 0,47 |
| 98 L2 0,37 |
| 99 L1 0,25 |

### Life Adjustment factor for operating conditions - aISO

The Bearing Dynamic Capacity formula was empirically determined through carefully controlled laboratory life testing. Many bearing applications are far from laboratory conditions. Therefore, it can be difficult to justify an $a_3$ factor greater than 1.0. Conditions such as high temperature, contamination, exterior vibration, etc. will lead to an a3 factor less than 1. If the lubrication is superior and the operating speed high enough, a significant improved lube film can develop between the bearing's internal contact surfaces justifying an a3 factor greater than 1.0. To safely use this benefit for design or commercial reasons requires a thorough analysis and either test data or previous experience.

$$(22)\ a_{iso} = f\left(\frac{e_c c_u L_{10}}{P}, k\right)$$

$e_C$ cleanliness, $C_u$ fatigue load limit, $L_{10}$ basic dynamic life, k viscosity ratio $\nu/\nu_1$ where $\nu_1$ is reference kinematic viscosity required to obtain adequate lubrication conditions.

To use this adjustment factor, information from SKF catalogues can be used. They call it $a_{SKF}$ [18].

**Full system Life – Gearbox Life**

Most machines employ two or more bearings on a shaft, and often there are two or more shafts. All the bearings in a machine are then considered to be a bearing system. It is important to combine the $L_{10}$ lives of all the bearings in the system to obtain the full system life and answer the question "How long will the machine perform with 90 percent reliability?" In simpler terms, the system $L_{10}$ reliability will be less than the lowest individual $L_{10}$ rating life. The following formula is used to calculate the System Rating Life:

$$(23)\ L_{10sys} = (L_1^{-w} + L_2^{-w} + \ldots L_n^{-w})^{-1/w}$$

where

- $L_{10sys}$ = rating life for the system of bearings
- $L_1$, $L_2$, $L_n$ = rating life for the individual bearings in the system
- w = 10/9 for ball bearings and
- w = 9/8 for roller bearings

TABLE 3-8: SYSTEM RELIABILITY FIGURE AND APPROXIMATE NUMBER OF CONSEQUENTIAL GEARBOX EXCHANGES OR REPAIRS.

| Reliability Rssr,20 (%) | #Gearbox exchanges/repairs per gearbox or 20 years |
|---|---|
| 95 | 0,05 |
| 90 | 0,11 |
| 80 | 0,22 |
| 70 | 0,32 |
| 60 | 0,45 |
| 50 | 0,59 |
| 40 | 0,72 |
| 30 | 0,89 |
| 20 | 1,09 |
| 10 | 1,35 |
| 5 | 1,54 |
| 1 | 1,85 |

### 3.2.5.3.4 Cost assessment

Based on a query to suppliers, the default cost has been defined as 55.88 € / kW

### 3.2.5.3.5 Environmental Impact

The following equation has been considered to obtain the mass of the gearbox:

$$(24)\ Mass = 6{,}9948 * P_{nom} + 1647{,}5$$

#### 3.2.5.3.6 Catalogue

**TABLE3-9: CATALOGUE OF GEARBOX**

| Element | Description |
|---|---|
| Power loads norm | Power load normalized to obtain different efficiencies |
| Eff levels | Efficiency per different power loads |
| Speed levels | Speed levels normalized with the nominal power to obtain different life levels |
| Life levels | Life levels per normalized speed |
| Cost | Cost per nominal power |
| Mass | Mass per nominal power |
| Failure rate cpx1 | Failure rate at complexity level 1 |

## 3.2.6 Electrical transformation

The objective of this module is the design of the components for grid conditioning electrical power: mainly the selection of the power converter, computes its efficiency, reliability cost and environmental issues.

### 3.2.6.1 Performance

The generator model is based on the calculation method for squirrel cage induction generator (SCIG). Its efficiency has been determined by calculating different losses:

- Mechanical losses
- Iron losses
- Winding losses.

### 3.2.6.2 Mechanical losses

Mechanical losses are consequences of bearing friction, and have been adjusted from the friction losses in the bearings [19]. In turn, friction losses in the bearings are defined as functions of the rotational speed and the shaft diameter as shown in Figure 3.18

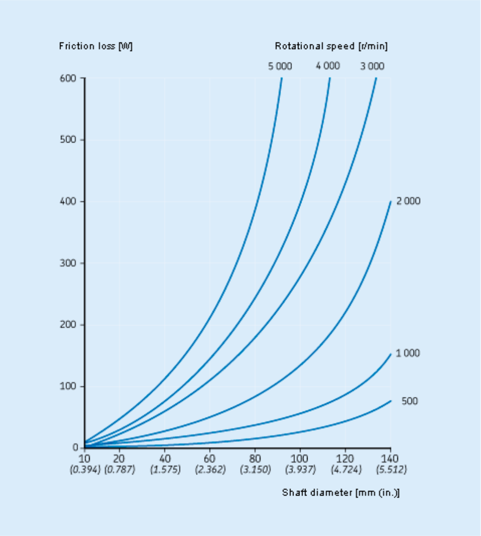


**FIGURE 3.18: MECHANICAL LOSES IN BEARINGS [19]**

Mechanical losses are a function of the shaft diameter, which in case of the ABB generators varies with the nominal power as described in [20],[21]:

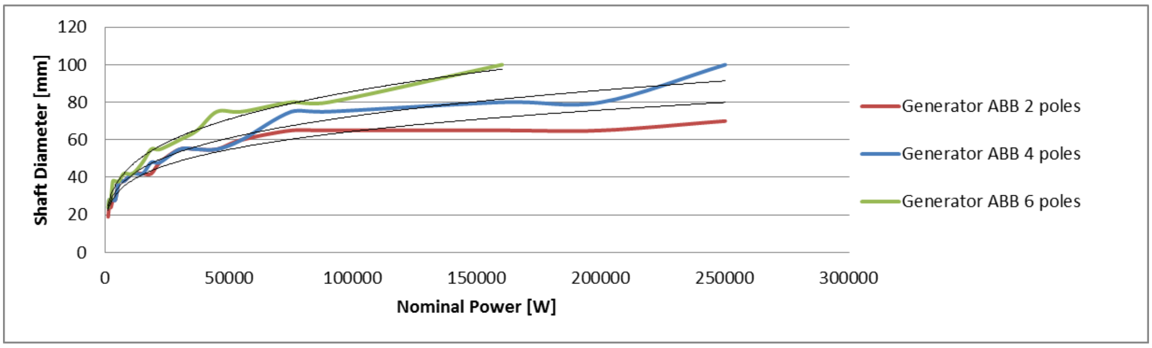


**FIGURE 3.19: MECHANICAL LOSSES ARE A FUNCTION OF THE SHAFT DIAMETER [20]**

#### 3.2.6.2.1 Iron Losses

Iron losses have been calculated per unit of mass, as [22]:

$$(25)\ w_f = B^2 \cdot \left\{ \sigma_h \cdot \left(\frac{f}{100}\right) + \sigma_e \cdot d^2 \cdot \left(\frac{f}{100}\right)^2 \right\}\ (W/kg)$$

Where:

- B: Average magnetic flux density in the air gap, considered to be of 0.8 [23]
- $\sigma_h$: Hysteresis loss coefficient
- $\sigma_e$: Eddy current loss coefficient
- $d$: Thickness of the iron core steel plate [mm]
- $f$: Frequency (Hz)

The thickness of the iron core has been considered to be the maximum with which it is manufactured, 0.64mm [24] and the frequency is the rotational speed times the pairs of poles of the generator.

Regarding the hysteresis and eddy current loss factors, a fitting has been made of the generator presented in [25], having obtained 5.01[-] and 44.8[-] factors respectively.

The absolute value of the generator losses must be calculated through the mass of the stator and rotor, which have been assumed to be of 60% of the total mass of the generator.

#### 3.2.6.2.2 Winding losses

Winding losses have been derived from the resistance of the stator and the RMS current in the stator (rotor Joule losses will be ignored) as:

$$(26)\ P_{loss,wind} = I_{est}^2 \cdot R_{est}$$

The resistance in stator has been fitted with available values at [26]:

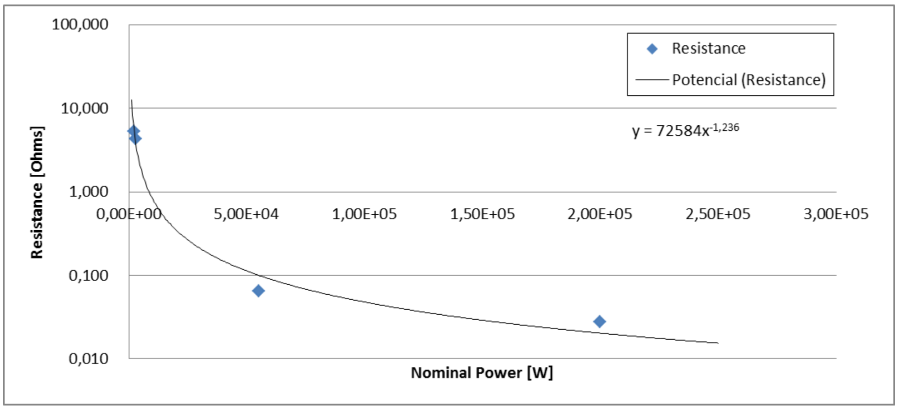


FIGURE 3.20: RESISTANCE DEPENDING ON THE NOMINAL POWER

The current along the generator stator is computed as:

$$(27)\ I_l = \frac{P_{IN\_mech}}{\sqrt{3} \cdot V_{LL} \cdot \cos\varphi}$$

Where:

$$(28)\ P_{IN\_mech} = \omega_{shaft} \cdot T_{IN}$$

The electric voltage considered is the nominal value, 400V given in [20].

Therefore, the efficiency is defined for each nominal power of the motor and its working conditions, $\omega_{shaft}$ and $P_{IN\_mech}$.

In relation with the control of the generator, its voltage is raised up to 690V linearly so that it works without losing torque capacity up to rotational speed larger than that of the nominal speed. For speeds higher than the mentioned value the torque is considered to be lowered with the square of the over speed, as shown below for different number of poles [27] as shown in Figure 3.24.

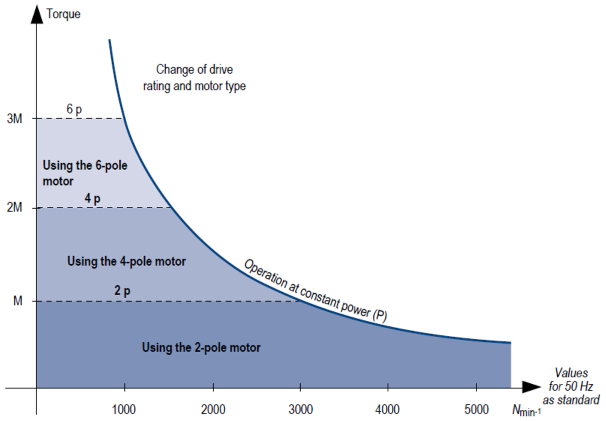


FIGURE 3.21: OPERATION AT CONSTANT POWER FOR DIFFERENT NUMBER OF POLES [27]

### 3.2.6.3 Reliability

The lifetime of a generator can be estimated studying the insulation which are estimated by statistical methods [23]. The machines may withstand temporary, often-repeated high temperatures depending on the duration and height of the temperature peak. A similar shortening of the lifetime applies also to the bearings of the motor, in which heat-resistant grease can be employed.

The generator life is calculated using the mean temperature of the generator given the stator current. Specifically, the total damage on the generator is computed as the sum of the individual damages for each operational sea state.

Generator life can be defined from the curves presented in Figure 3.25, which depend on the class of the generator and winding temperature:

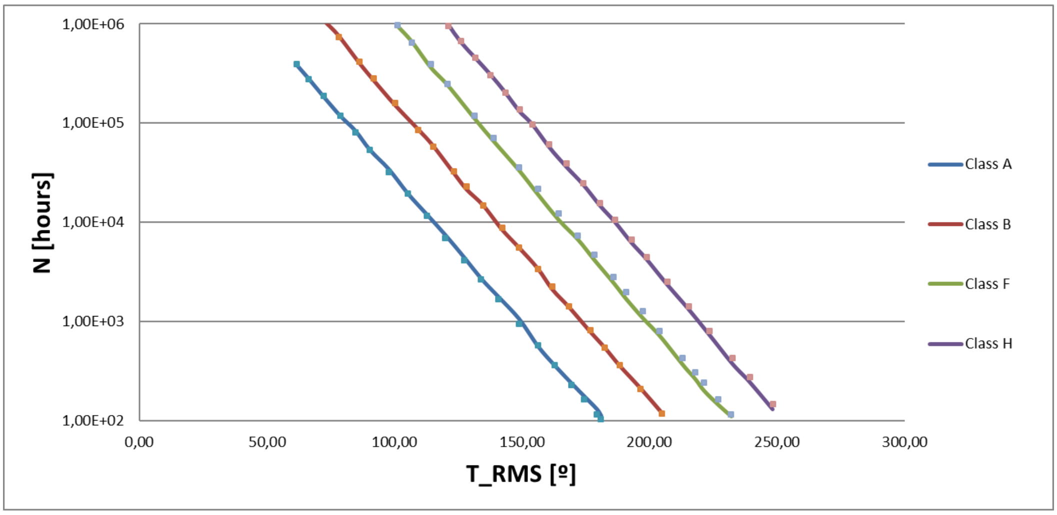


FIGURE 3.22: TOTAL WINDING TEMPERATURE CURVES OBTAINED FROM [28]

Curves of the figure above have been adjusted through logarithmic functions, having obtained the following results: $N = e^{KT+K0}$

TABLE 3-10: LIFE ASSESSMENT CURVES ADJUSTMENT

| Life assess adjust | Class A | Class B | Class F | Class H |
|---|---|---|---|---|
| **K** | -0,069 | -0,069 | -0,069 | -0,069 |
| **Ko** | 17,1288228 | 18,8974785 | 20,7619675 | 22,1243926 |
| **$T_{max}$** | 105 | 130 | 155 | 180 |

(29) $T_{RMS}=K^*I_{RMS}^2$

The relation, k, between the RMS current and temperature has been supposed to be the corresponding value to be working at the maximum permissible temperature and the nominal current.

#### 3.2.6.4 Cost assessment

According to internal inquiries in Tecnalia, the generator cost will be around 80€/kW (considered as a default value, but user could modify at complexity level 3)

#### 3.2.6.5 Environmental Impact

The following Table 3-11 shows a relation of kg of material for the generator

TABLE 3-11: RELATION OF KG OF MATERIAL OF A GENERATOR [29]

| Type of Material | kg/kW |
|---|---|
| Electro steel | 0,980 |
| Normal rolled steel | 1.492 |
| Special steel | 0.201 |
| Cast iron | 0.056 |
| Aluminium | 0.007 |
| Copper | 0.350 |
| Insulation material | 0.051 |
| Wooden boxes and planks | 0.195 |
| Impregnation resin | 0.025 |
| Paint | 0.002 |
| TOTAL | 3,35 |

TABLE 3-12: RELATION OF KG OF MATERIAL GENERATOR CATALOGUE [30]

| Type of materials | Kg/kVA | |
|---|---|---|
| | AMG 450 | AMG 630 |
| Electrical steel | 2.97 | 2.17 |
| Other steel | 2.60 | 1.44 |
| Copper | 0.59 | 0.24 |
| Insulation material | 0.02 | 0.05 |
| Impregnation resin | 0.03 | 0.03 |
| Paint | 0.01 | 0.01 |
| Solvent | 0.01 | 0.01 |

#### 3.2.6.6 Catalogue

The definition of either specific SCIG or a set of them is assumed to be done through a user defined catalogue. The required fields are broken down into 3 categories:

TABLE 3-13: CATALOGUE OF THE GENERATOR

| Parameter | Description |
|---|---|
| **General information** | |
| ID | |
| Material | |
| Date | |
| Manufacturer | |
| Mass | |
| Cost | |
| **Constructive parameters** | |
| Power rated | |
| Tension rated | |
| I rated | |
| F rated | |
| T max | Maximum torque |
| V max | Maximum voltage |
| Pp | Pair of poles |
| Shaft diam | Diameter of the shaft in the generator, which allocates the rotor |
| R_stat: | Resistance of the stator [ohms] |
| Sigma_e and sigma_h | eddy current and hysteresis loss coefficients as defined in equation (25). |
| B | Average magnetic field in the airgap |
| **Reliability parameters** | |
| K | corresponding parameters, as defined in 0, to calculate the damage in the generator. |
| Ko | |
| T max | |

### 3.2.7 Grid conditioning

A back to back two-level power converter (BTB2L) has been considered. The topology is shown in Figure 3.26Figure . In consists of two equal Insulated Gate Bipolar Transistor (IGBT) bridges connected through a Direct Current DC-bus (capacitance).

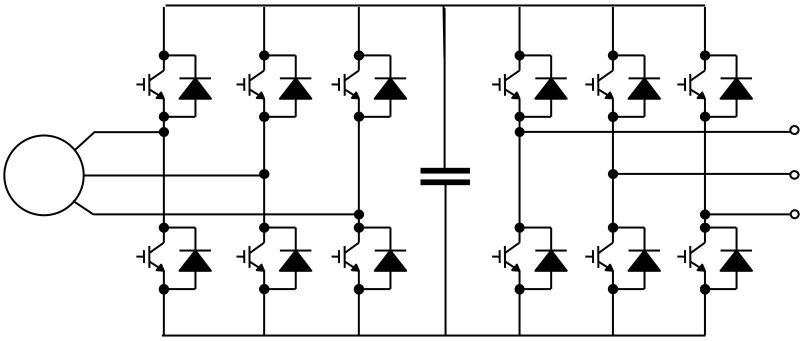


FIGURE 3.23: BACK-TO-BACK 2 LEVEL POWER CONVERTER TOPOLOGY

#### 3.2.7.1 Performance

The efficiency calculation method consists in calculating the losses of each of the converters and subtracting them from the input power. The losses considered in this model are the following:

- IGBT switching losses
- IGBT conduction losses
- Diode switching losses
- Diode conduction losses
- Joule losses in the filter

Blocking (leakage) losses have been neglected.

Total losses will be the sum of the set of previous losses.

Each converter has 6 IGBTs and 6 diodes, thus, the switching and conduction losses of one single device are calculated and then multiplied by 6 in each converter.

##### 3.2.7.1.1 Power modules from datasheet

For the power losses calculation, the most suitable semiconductor modules must be selected depending on the input nominal parameters. The following modules have been used and their data extracted for each input power range.

**TABLE 3-14: POWER MODULES FOR EFFICIENCY CALCULATION (FROM MANUFACTURERS DATASHEET [32])**

| | $V_{CE}$ | $V_{CE}$ design | Ic nom | Ic design | P max |
|---|---|---|---|---|---|
| INFINEON FF150R17KE4 | 1700 V | 1200 V | 150 A | 75 A | 110 kW |
| INFINEON FF450R17IE4 | 1700 V | 1200 V | 450 A | 225 A | 330 kW |
| ABB 5SNE 0800M170100 | 1700 V | 1200 V | 800 A | 400 A | 587 kW |
| ABB 5SNA 1600N170100 | 1700 V | 1200 V | 1600 A | 800 A | 1175 kW |

For safety reasons, a conservative approach has been adopted. The maximum current and voltage data defined as *Ic design* and *$V_{CE}$ design* are considered valid and will correspond to the maximum current and the maximum bus voltage value admitted.

For calculating conduction and switching losses, the methodology shown in [31] has been followed. As an example on how to find the needed parameters from a datasheet, the power module ABB 5SNE 0800M170100 [32] has been taken.

#### 3.2.7.1.2 IGBT Looses

1 IGBT Conduction losses

The IGBT conduction losses are calculated with the following equation:

$$(30)\ P_{ci} = \frac{1}{2}\left(V_{CEO} \cdot \frac{\hat{\imath}}{\pi} + r_{CE} \cdot \frac{\hat{\imath}^2}{4}\right) + m \cdot cos\emptyset \cdot \left(V_{CEO} \cdot \frac{\hat{\imath}}{8} + \frac{1}{3\pi} \cdot r_{CE} \cdot \hat{\imath}^2\right)$$

Where:

- $P_{ci}$ are the conduction losses of a single IGBT
- $V_{CEO}$ is the on-state zero-current collector-emitter voltage of the IGBT
- $r_{CE}$ is the collector emitter on-state resistance
- $m$ is the modulation index of the power converter
- $cos\emptyset$ is the power factor
- $\hat{\imath}$ is the current

These parameters can be read directly from the IGBT Datasheet as seen in Figure 3.24. In order to take the parameter variation into account, and thus to have a conservative calculation, $V_{CEO}$value read from the diagram has to be scaled with (Vcemax/Vcetyp) value. Those exact values can be read from the datasheet tables, but for an engineering calculation a typical safety margin value of (1.1-1.2) can be used.

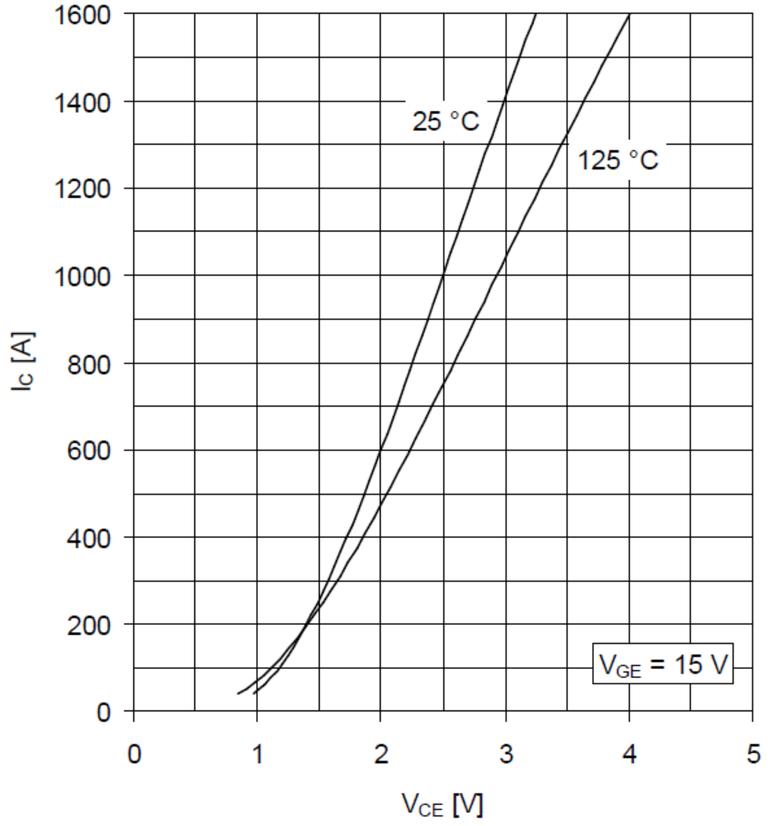


**FIGURE 3.24: READING THE $V_{CEO}$ AND $r_{CE}$ (RC =ΔUCE/ ΔIC) FROM THE DATA-SHEET DIAGRAM [32]**

Usually, the highest temperature curve is used.

1 IGBT Switching losses

The switching losses in the IGBT are the product of switching energies and the switching frequency (fsw). The switching energies are the sum of switch-on and switch-off energies.

$$(31)\ P_{swi} = f_{sw} \cdot (E_{oni} + E_{offi})$$

Information about the switch on and switch off energies can be found in the manufacturer datasheet as in Figure 3.28. Parameters a, b and c, are the coefficients of the approximated curve. If manufacturer does not provide them, they can be calculated from the curve. The switching losses are then calculated from the following equation:

$$(32)\ P_{swi} = f_{sw} \cdot \left(\frac{a}{2} + \frac{b \cdot \hat{\imath}}{\pi} + \frac{c \cdot \hat{\imath}^2}{4}\right) \cdot \frac{V_{DC}}{V_{nom}}$$

Where:

- $P_{swi}$ are the switching losses of a single IGBT
- $V_{DC}$ is the voltage of the DC link
- $f_{sw}$ is the switching frequency
- $V_{nom}$ is the nominal voltage

- $\hat{\imath}$ is the current

These parameters can be obtained from the datasheet [32] as shown in Figure 3.25:

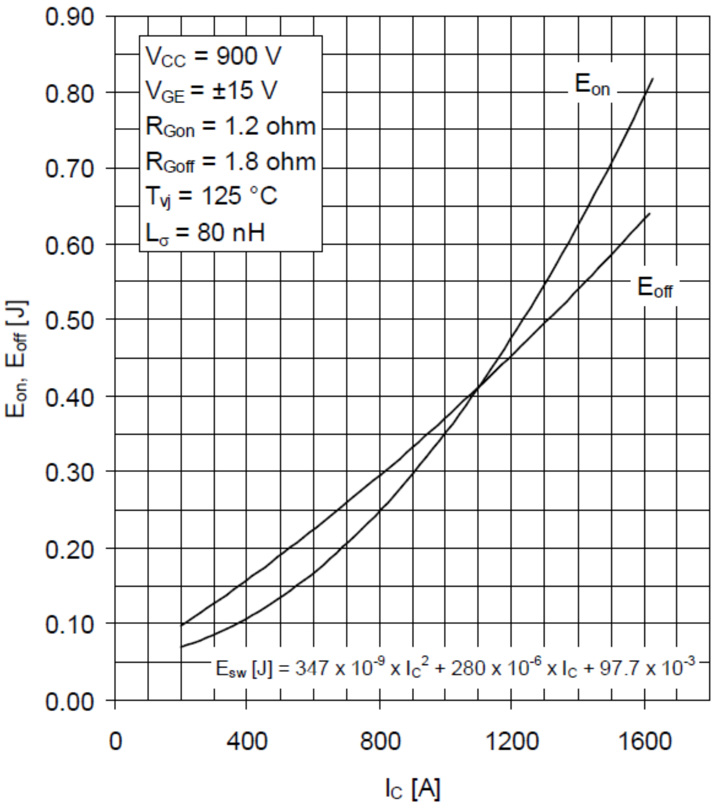


FIGURE 3.25: TYPICAL SWITCHING ENERGIES PER PULSE VS COLLECTOR CURRENT [32]

### 3.2.7.1.3 Diode Looses

<u>1 Diode Conduction losses</u>

Using the same approximation for the anti-parallel diode, the conduction losses are calculated from the following equation:

$$(33)\ P_{cd} = \frac{1}{2}\left(V_{FO} \cdot \frac{\hat{\imath}}{\pi} + r_T \cdot \frac{\hat{\imath}^2}{4}\right) - m \cdot cos\emptyset \cdot \left(V_{FO} \cdot \frac{\hat{\imath}}{8} + \frac{1}{3\pi} \cdot r_T \cdot \hat{\imath}^2\right)$$

Where:

- $P_{cd}$ are the conduction losses of a single diode
- $V_{FO}$ is the zero-current forward voltage of the IGBT
- $r_T$ is the forward resistance
- $m$ is the modulation index of the power converter
- $cos\emptyset$ is the power factor

Again, the main parameters are obtained from the manufacturer datasheet as shown in Figure 3.29.

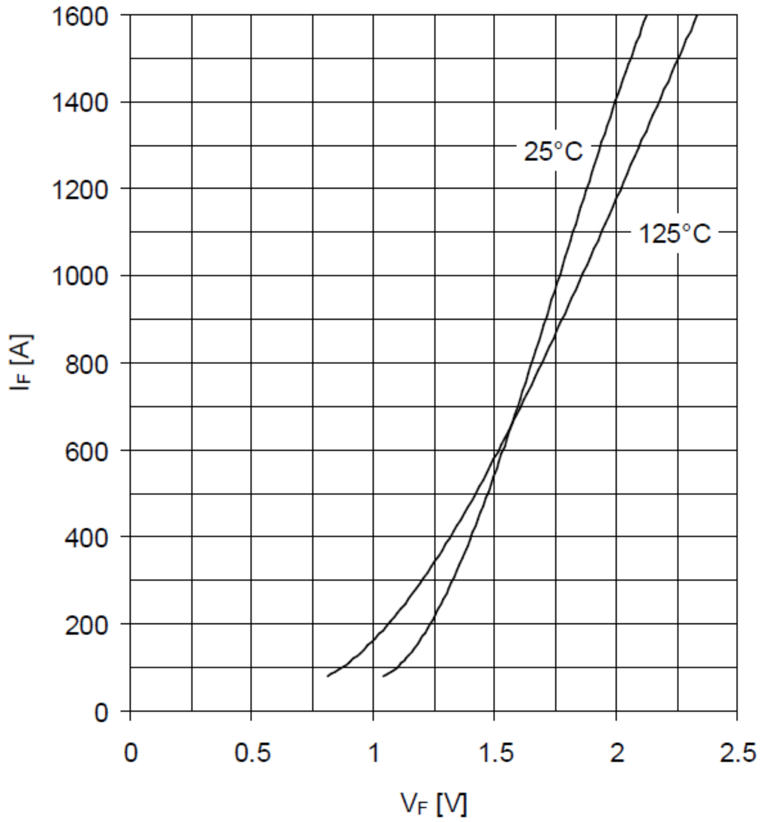


FIGURE 3.26: OBTAINING $V_{FO}$ AND $r_T$ PARAMETERS FROM THE DATASHEET [32]

1 Diode Switching losses

The following equation represents the diode switching losses:

$$(34)\ P_{swd} = f_{sw} \cdot \left(E_{ond} + E_{offd}\right)$$

But the switch of losses of the diode can be neglected. The turn-on energy in the diode consists mostly of the reverse-recovery energy ($E_{rec}$) and the curve can again be found on the datasheet as in Figure 3.30.

Again, the same methodology as for the IGBT is used giving the following equation:

$$(35)\ P_{swd} = f_{sw} \cdot \left(\frac{a}{2} + \frac{b \cdot \hat{\imath}}{\pi} + \frac{c \cdot \hat{\imath}^2}{4}\right) \cdot \frac{V_{DC}}{V_{nom}}$$

Where:

- $P_{swd}$ are the switching losses of a single diode
- $V_{DC}$ is the voltage of the DC link
- $f_{sw}$ is the switching frequency
- $V_{nom}$ is the nominal voltage
- $\hat{\imath}$ is the current

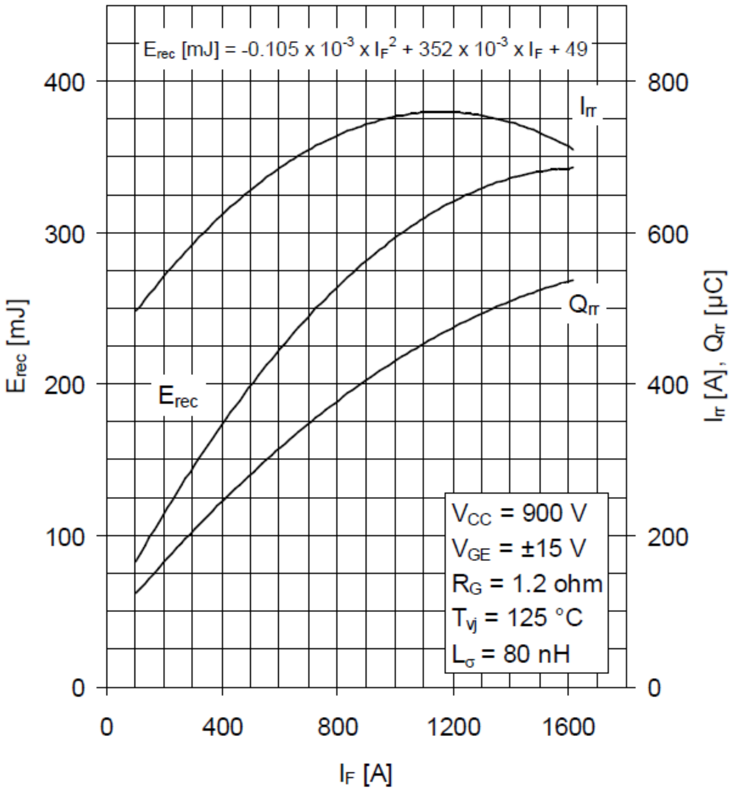


**FIGURE 3.27: TYPICAL REVERSE RECOVERY CHARACTERISTICS VS FORWARD CURRENT [32]**

In the case of diodes, switch off losses are usually neglected, the switching losses are the product of switch on energy and the switching frequency (fsw).

### 3.2.7.1.4 Total Looses and Efficiency calculation

As the current that circulates for each power converter is different, the losses of the generator-side converter (rectifier) and grid-side converter (inverter) are calculated separately. In both cases the equation will be:

$$(36)\ P_{r,i} = 6 \cdot (P_{ci} + P_{cd} + P_{swi} + P_{swd})$$

Where $P_r$ are the power losses of the rectifier (generator-side converter)

But each of the losses must be calculated with the proper current. The output current from the generator (rectifier) or the current injected to the grid (inverter).

The output current from the generator is obtained from the input power and input generator voltage. For calculating the grid side current, we must consider the power loss in both converters that will make the grid side current be lower. As we don't know yet the power losses of the inverter, we assume for the current calculation that they are the same as in the rectifier.

$$(37)\ P_{grid} \approx P_{gen} - P_r - P_r$$

Where $P_{grid}$ is the output power from the B2B converter, thus, the power injected to grid. Therefore, the current injected to grid that will be used for the losses calculation in the inverter is:

$$(38)\ i_{grid} = \frac{\sqrt{2}}{\sqrt{3}} \frac{P_{grid}}{V_{grid}}$$

Considering that $V_{grid}$ is rms and $i_{grid}$ is peak amplitude.

Then, the efficiency of the whole B2B converter will be:

$$(39)\ Eff_{B2B} = \frac{P_{gen} - P_r - P_i}{P_{gen}}$$

### 3.2.7.2 Reliability

The lifetime data is usually given in two lifetime curves. One is for a slow cycle period ($t_{cycle}$=2min) and other one for a fast cycle ($t_{cycle}$=2s), these curves are valid for all the power converter modules. The lifetime curves represent the critical joins, each of which fail due to different failure mechanisms [33],[34]

The lifetime of power converter modules is assessed by power cycling experiments, where a given temperature is repetitively applied to a module until it fails. The failure criterium is defined as a 5% increase in $V_{CB}$.

The temperature cycles are defined as the maximum-minimum values of a cycle [33] and a Weibull distribution (two parameters) is used to define the lifecycle $B_{10}$ (number of cycles where 10% of the modules fail [35]). The typical life models used are based on Coffin-Manson law and fatigue due a plastic deformation [36].

Three models can describe de lifetime:

- Chip solder joint
- Solder joints of the conductor
- Wire bonds

For this study taking into account that the model has been developed in frequency domain, the supposition of time independent has been adopted, considering the averages ranges obtained from catalogues (cycle period $T_{cycle}$=30s ,*minimum* temperature $T_{cmin}$ =40º, absolute maximum temperature $T_{j,max}$=125º and ) [33]. Considering that $T_{cmin}$=40º and $T_{j,max}$=125º

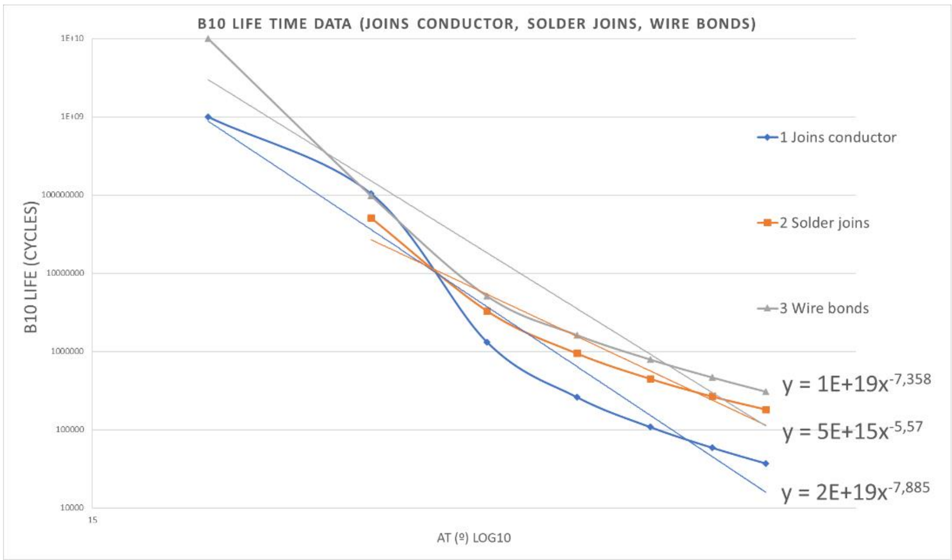


FIGURE 3.28: B10 LIFETIME DATA (JOINS CONDUCTOR, SOLDER JOINS AND WIRE BONDS)

Figure 3.28 shows B10 lifetime data for joins conductor, solder points and wire bonds. For this study, the worst scenario has been considered, joins conductor.

#### 3.2.7.3 Cost assessment

Converter 100k€ / MW (default value selected based on queries with developers, user could modify at complexity level 3).

#### 3.2.7.4 Environmental Impact

Regarding environmental issues Table 3-15 represents the relation between Kg of material and power of the converter:

TABLE 3-15: RELATION OF KG OF MATERIAL AND POWER CONVERTER [37]

| Type of Material | kg/kW |
|---|---|
| Aluminium | 0.012 |
| Copper | 0.137 |
| Plastic | 0.060 |
| Steel | 0.326 |
| Iron | 0.005 |
| Zinc | 0.002 |
| Other | 0.061 |

#### 3.2.7.5 Catalogue

The definition of either specific back-to-back 2 level or a set of them is assumed to be done through a user introduced catalogue. The required fields are broken down into 3 categories:

TABLE 3-16: CATALOGUE OF POWER ELECTRONICS

| Parameter | Description |
|---|---|
| **General parameters** | |
| ID | |
| Material | |
| Date | |
| Manufacturer | |
| Mass | |
| Cost | |
| Constructive parameters | |
| P_rated: | Rated Power [W] of the back-to-back 2 level converter |
| $V_{CEO}$ | Is the on-state zero-current collector-emitter voltage of the IGBT |
| $r_{CE}$ | is the collector emitter on-state resistance of the IGBT |
| Vcc | is the nominal voltage |
| a, b and c | coefficients of the curve fitting of the reverse recovery energy curve given by the manufacturer |
| Rgen | generator resistance [Ω] (used for calculating the voltage at the input of the converter) |
| Lgrid | Inductance |
| Rgrid | resistance |
| Vgrid | Grid Voltage |
| $f_{sw}$ | Switching frequency [Hz] |
| **Reliability parameters** | |
| Ko | |
| K | |
| T_o | |
| T_rated | |
| T_max | |

### 3.2.8 Control Strategies

The control strategy in the Energy Transformation deployment tool consists in defining the probability distribution of the captured power and the corresponding loads, maintaining the same mean captured power and representing the PTO damping through the operational conditions of the mechanical transformation object.

The power distribution is needed to enable the computation of the efficiency of each transformation stage subject to each environmental condition. The loads in the mechanical conversion stage is subsequently used to provide an annual probability density function to RAMS so that the survivability can be computed. The load ranges are used in the ET module to compute the fatigue damage in each transformation stage.

The most simplistic approach is the passive control in which the PTO damping is assumed to be represented by a purely linear system. Some other control strategies are herein represented that produce different probability distributions and consequently modifying the efficiency of the energy transformation stages.

#### 3.2.8.1 Passive Control

The passive control assumes that the PTO force is applied as a purely linear damping force. Therefore, the motion probability density function (PDF) is represented by the same PDF of the excitation force. It is here assumed that the wave elevation (and the excitation force since only linear excitation force is considered) follows a Gaussian distribution with a mean zero value and so will be the motion of the wave energy converter. The produced power with the passive control strategy is computed as:

$$(40)\ P(t) = F_{pto}(t) \cdot v(t) = C_{pto} \cdot v(t)^2$$

It is known that the square of a Gaussian distributed variable is distributed as a chi-square ($\chi^2$) distribution of one degree of freedom, and, since the power is proportional to the square of the velocity it will also be $\chi^2$ distributed. Figure 3.29 shows an example of power distribution function for a specific sea states.

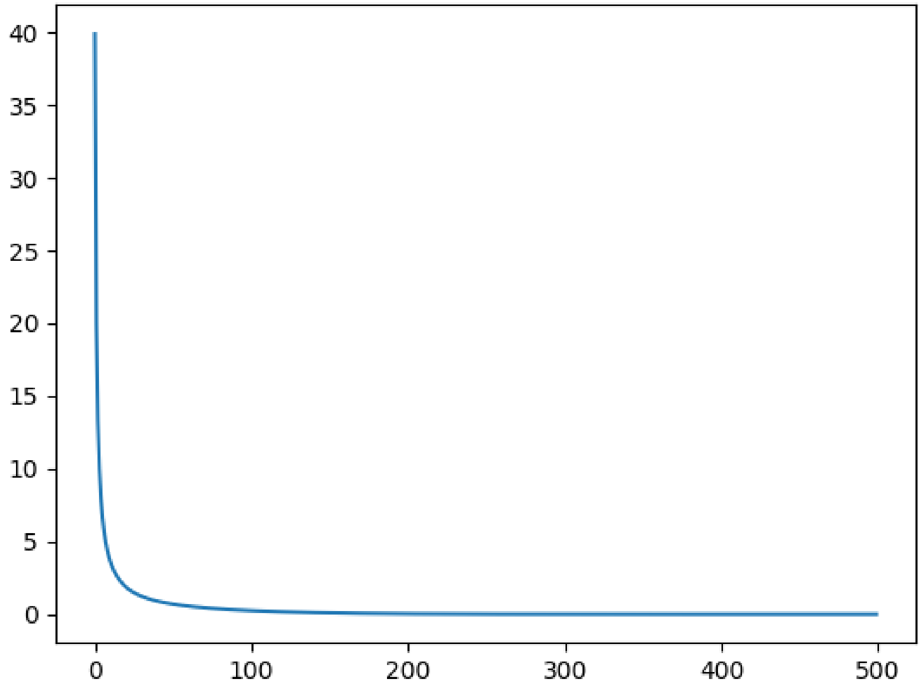


FIGURE 3.29: POWER DISTRIBUTION FUNCTION FOR AN SPECIFIC SEA STATE

The force is assumed to be rectified by the mechanical transformation stage which makes the force distributed as the absolute value of the velocity. Therefore, it follows a folded-normal distribution with zero mean velocity. Figure 3.30 shows an example of torque distribution function for a specific sea state.

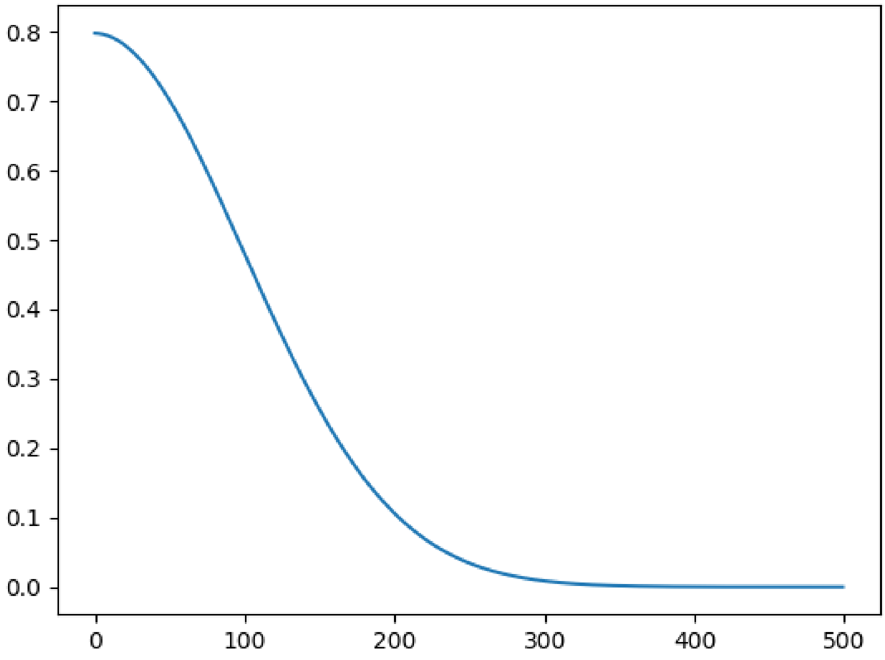


FIGURE 3.30: TORQUE DISTRIBUTION FUNCION FOR AN SPECIFIC SEA STATE

Also, since the velocity is Gaussian distributed, it is straightforward to assume that the force ranges follow a Rayleigh distribution.Figure 3.31 shows an example of probability torque range distribution for a sea state:

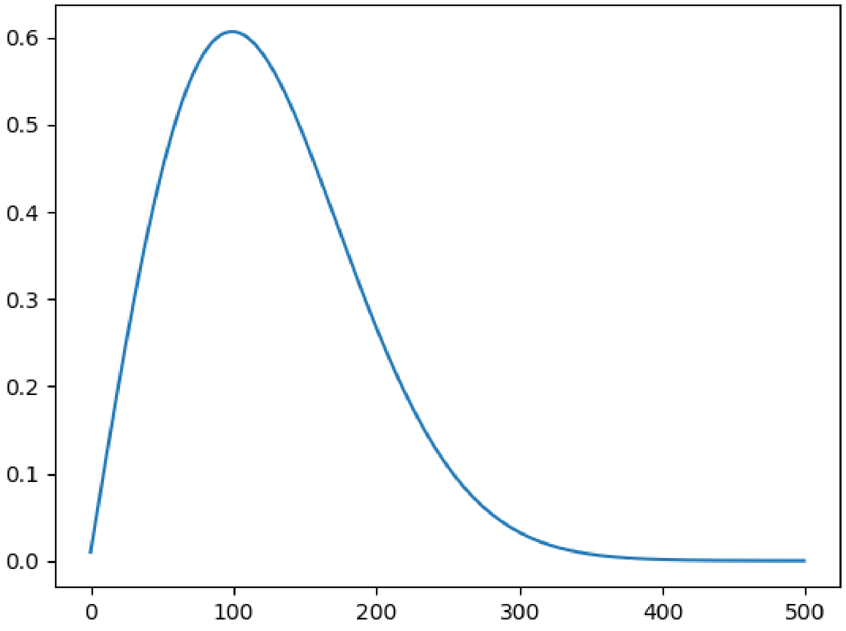


FIGURE 3.31: EXAMPLE OF A PROBABILITY TORQUE RANGE DISTRIBUTION FOR A SEA STATE

## 3.3 INPUTS AND OUTPUTS DEPENDING ON THE COMPLEXITY LEVELS

The relation of inputs is different depending on the complexity level. The next three tables, include the inputs required depending on the complexity level selected:

**TABLE 3-17: INPUTS AT COMPLEXITY LEVEL 1**

| Stage 0 | Stage 1 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| **Project level** | | |
| ET project ID | Module Internal Variable | |
| Number of devices | User input value | |
| Technology | User input value | |
| cmpx selection | User input value | Check requirements on conversion type related with the complexity levels at device level |
| Environmental Conditions (Hs/Tp/Occ - Vc/turb/Occ) | Module output - MC/SC | tbd yet the source module |
| **Device level** | | |
| Device ID | Module Internal Variable | |
| Number of PTOs per device (dof_ptos) | Module output - MC | OK |
| Number of PTOs per device (parallel_ptos) | User input value | OK |
| Hs/Vc cut-in/cut-out | Module output - MC | too advanced |
| Shutdown Flag | User input value | |
| Device Performance INPUTS | Module output - EC | Power & Force/Torque information. (Power and TSR at tidal device, power and Cpto at wave case) |
| Mechanical Conversion Type | Module dropdown | One out of these three must be 'Simplified' and None of them can be 'User specified' |
| Electrical Conversion Type | Module dropdown | |
| Grid Conditioning Type | Module dropdown | |
| **PTO level** | | |
| PTO ID | Module Internal Variable | |
| Mechanical Conversion Size (Max Power) | User input value | Simplified Mechanical Transformation |
| Mechanical Transmission Ratio | User input value | |
| Mechanical Efficiency | User input value | |

| Stage 0 | Stage 1 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| Electrical Conversion Rated Power | User input value | Simplified Electrical Transformation |
| Grid Conditioning Rated Power | User input value | Simplified Power Converter |

Inputs at complexity level 2:

TABLE 3-18: INPUTS AT COMPLEXITY LEVEL 2

| Stage 2 | Stage 3 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| **Project level** | | |
| ET project ID | Module Internal Variable | |
| Number of devices | User input value | |
| Technology | User input value | |
| CPX selection | User input value | Check requirements on conversion type related with the complexity levels at device level |
| Environmental Conditions (Hs/Tp/Occ - Vc/turb/Occ) | Module output - MC/SC | tbd yet the source module |
| **Devive level** | | |
| Device ID | Module Internal Variable | |
| Number of PTOs per device (dof_ptos) | Module output - MC | OK |
| Number of PTOs per device (parallel_ptos) | User input value | OK |
| Hs/Vc cut-in/cut-out | Module output - MC | too advanced |
| Shutdown Flag | User input value | |
| Device Performance INPUTS | Module output - EC | Power & Force/Torque information. (Power and TSR at tidal device, power and Cpto at wave case) |
| Mechanical Conversion Type | Module dropdown | All of them must be 'realistic', e.g. they cannot be not 'Simplified' nor 'User Specified' |
| Electrical Conversion Type | Module dropdown | |
| Grid Conditioning Type | Module dropdown | |

| Stage 2 | Stage 3 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| **PTO Level** | | |
| PTO ID | Module Internal Variable | |
| Turbine_Type | Module dropdown | Realistic Air Turbine |
| Turbine_Diameter | User input value | |
| Turbine_OWC_Surface | User input value | |
| Turbine_transmission_ratio | User input value | |
| Hydraulic_Size | User input value | Realistic Hydraulic System |
| Hydraulic_piston_Area | User input value | |
| Hydraulic_transmission_ratio | User input value | |
| Gearbox_P_rated | User input value | Realistic Gearbox |
| Gearbox_transmission_ratio | User input value | |
| SCIG_P_rated | User input value | Realistic Squirrel Cage Induction Generator |
| SCIG_pairs_of_poles | User input value | |
| SCIG_Rated_Voltage | User input value | |
| SCIG_Rated_frequency | User input value | |
| SCIG_Maximum_Torque_ratio | User input value | |
| SCIG_Maximum_Voltage_ratio | User input value | |
| SCIG_Class | User input value | |
| B2B2Level_P_rated | User input value | Realistic Back to Back to Level (Power Converter) |
| B2B2Level_Vdc | User input value | |
| B2B2Level_switching_frequency | User input value | |
| B2B2Level_Grid_Voltage | User input value | |
| B2B2Level_Grid_Resistance | User input value | |
| B2B2Level_cosphi | User input value | |

Inputs at complexity level 3:

TABLE 3-19: INPUTS AT COMPLEXITY LEVEL 3

| Stage 4 | Stage 5 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| **Project level** | | |
| ET project ID | Module Internal Variable | |
| Number of devices | User input value | |
| Technology | User input value | |
| CPX selection | User input value | Check requirements on conversion type related with the complexity levels at device level |
| Environmental Conditions (Hs/Tp/Occ - Vc/turb/Occ) | Module output - MC/SC | |
| **Device level** | | |
| Device ID | Module Internal Variable | |
| Number of PTOs per device (dof_ptos) | Module output - MC | OK |
| Number of PTOs per device (parallel_ptos) | User input value | OK |
| Hs/Vc cut-in/cut-out | Module output - MC | too advanced |
| Shutdown Flag | User input value | |
| Device Performance INPUTS | Module output - EC | Power & Force/Torque information. (Power and TSR at tidal device, power and Cpto at wave case) |
| Mechanical Conversion Type | Module dropdown | One out of these three must be 'User specified' and None of them can be 'Simplified' |
| Electrical Conversion Type | Module dropdown | |
| Grid Conditioning Type | Module dropdown | |
| **PTO level** | | |
| PTO ID | Module Internal Variable | |
| Turbine_Type | Module dropdown | User Specified Air Turbine |
| Turbine_Diameter | User input value | |
| Turbine_OWC_Surface | User input value | |
| Turbine_transmission_ratio | User input value | |
| Turbine_ID | User input value | |
| Turbine_Material | User input value | |

| Stage 4 | Stage 5 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| Turbine_Date | User input value | |
| Turbine_Manufacturer | User input value | |
| Turbine_Velocity | User input value | |
| Turbine_Pressure drop | User input value | |
| Turbine_Torque | User input value | |
| Turbine_m1 | User input value | |
| Turbine_log(a1) | User input value | |
| Turbine_m2 | User input value | |
| Turbine_log(a2) | User input value | |
| Turbine_mass | User input value | |
| Turbine_cost | User input value | |
| Turbine_shaftDiam | User input value | |
| Hydraulic_Size | User input value | User Specified Hydraulic System |
| Hydraulic_piston_Area | User input value | |
| Hydraulic_transmission_ratio | User input value | |
| Hydraulic_Hydr Loss coeff (piping) | User input value | |
| Hydraulic_Motor flow control | User input value | |
| Hydraulic_Oil Viscosity | User input value | |
| Hydraulic_Oil density | User input value | |
| Hydraulic_Laminar leakage coeff | User input value | |
| Hydraulic_Bulk Mod | User input value | |
| Hydraulic_Turbulent leakage coeff | User input value | |
| Hydraulic_Viscous loss coeff | User input value | |
| Hydraulic_Friction loss coeff | User input value | |
| Hydraulic_Hydr Loss coeff (motor) | User input value | |
| Hydraulic_Shaft Diam | User input value | |
| Hydraulic_Mass | User input value | |
| Hydraulic_m1 | User input value | |
| Hydraulic_log(a1) | User input value | |
| Hydraulic_m2 | User input value | |
| Hydraulic_log(a2) | User input value | |
| Hydraulic_cost | User input value | |
| Gearbox_Rated Power | User input value | User Specified Gearbox |
| Gearbox_Power Factor | User input value | |
| Gearbox_efficiency | User input value | |
| Gearbox_Shaft Diam | User input value | |
| Gearbox_Mass | User input value | |
| Gearbox_m1 | User input value | |

| Stage 4 | Stage 5 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| Gearbox_log(a1) | User input value | |
| Gearbox_m2 | User input value | |
| Gearbox_log(a2) | User input value | |
| Gearbox_cost | User input value | |
| SCIG_Conversion Rated Power | User input value | User Specified SCIG |
| SCIG_Shaf diameter | User input value | |
| SCIG_Res (ohm) | User input value | |
| SCIG_mass (kG) | User input value | |
| SCIG_B | User input value | |
| SCIG_sigma h (-) | User input value | |
| SCIG_sigma e (-) | User input value | |
| SCIG_phi cos (0-1) | User input value | |
| SCIG_k (for life assessment) (-) | User input value | |
| SCIG_ko (for life assessment) (-) | User input value | |
| SCIG_Temp max (for life assessment) (degrees) | User input value | |
| SCIG_cost per kW (€) | User input value | |
| SCIG_Pairs of poles | User input value | |
| SCIG_Tmax (Nm) | User input value | |
| SCIG_Vmax (V) | User input value | |
| SCIG_Pnom (W) | User input value | |
| SCIG_Vnom (V) | User input value | |
| SCIG_Inom (A) | User input value | |
| SCIG_manufacturer | User input value | |
| SCIG_date | User input value | |
| B2B2Level_Rated Power | User input value | User Specified B2B2Level |
| B2B2Level_R grid (ohm) | User input value | |
| B2B2Level_V grid (V) | User input value | |
| B2B2Level_cosphi | User input value | |
| B2B2Level_IGBT_Vceo (V) | User input value | |
| B2B2Level_IGBT_Rce (ohm) | User input value | |
| B2B2Level_Vcc (V) | User input value | |
| B2B2Level_IGBT_a_fit | User input value | |
| B2B2Level_IGBT_b_fit | User input value | |
| B2B2Level_IGBT_c_fit | User input value | |
| B2B2Level_Diode_Vdc (V) | User input value | |
| B2B2Level_Diode_a_fit | User input value | |
| B2B2Level_Diode_b_fit | User input value | |
| B2B2Level_Diode_c_fit | User input value | |

| Stage 4 | Stage 5 | |
|---|---|---|
| **Parameters required** | **Source (choose from dropdown list)** | **Additional Information** |
| B2B2Level_f_sw (Hz) | User input value | |
| B2B2Level_k (for life assessment) (-) | User input value | |
| B2B2Level_ko (for life assessment) (-) | User input value | |
| B2B2Level_Temp max (for life assessment) (degrees) | User input value | |
| B2B2Level_Temp rated (for life assessment) (degrees) | User input value | |
| B2B2Level_manufacturer | User input value | |
| B2B2Level_date | User input value | |

TABLE 3-20: OUTPUTS AT COMPLEXITY LEVEL 3

| Parameter | Units | Additional Information |
|---|---|---|
| **Array level** | | |
| Array ID | **Module Internal Variable** | |
| Technology | - | Wave/Tidal |
| Number of Devices | - | |
| Bill of Materials | - | |
| Hierarchy | - | |
| Complexity Level | - | |
| Environmental Conditions | - | Used for the Transformation, but taken from SC/EC |
| Array Cost | [€] | |
| Array Mass | [kg] | |
| Array Annual Mean Mechanical Power | [W] | |
| Array Annual Mean Electrical Power | [W] | |
| Array Annual Mean Grid Conditioned Active Power | [W] | |
| Array Annual Mean Grid Conditioned Reactive Power | [VaR] | |
| Array Annual Transformed Mechanical Energy | [Wh] | |
| Array Annual Transformed Electrical Energy | [Wh] | |
| Array Annual Grid Conditioned Energy | [Wh] | |
| **Device level** | | |
| Device ID | **Module Internal Variable** | |
| Technology | **-** | |
| Number of PTOs per device (degrees of freedom) | - | |
| Number of PTOs per device (parallel) | - | |

| Parameter | Units | Additional Information |
|---|---|---|
| Cut-in / Cut-out | [m] / [m/s] | |
| ShutDown Flag | - | |
| Control Strategy | - | |
| Device output Voltage | [V] | |
| Mechanical Conversion Type | - | |
| Electrical Conversion Type | - | |
| Grid Conditioning Type | - | |
| PTO Cost | [€] | |
| PTO Mass | [kg] | |
| Device Annual Transformed Mechanical Power | [W] | |
| Device Annual Transformed Electrical Power | [W] | |
| Device Annual Grid Conditioned Active Power | [W] | |
| Device Annual Grid Conditioned Reactive Power | [VaR] | |
| Device Annual Mechanical Transformed Energy | [Wh] | |
| Device Annual Electrical Transformed Energy | [Wh] | |
| Device Annual Grid Conditioned Energy | [Wh] | |
| **PTO level** | | |
| PTO ID | **Module Internal Variable** | |
| Mechanical Conversion Size | [W] | |
| Mechanical Conversion Cost | [€] | |
| Mechanical Conversion Mass | [kg] | |
| Mechanical Mean Transformed Power | [W] | |
| Mechanical Transformed Energy | [Wh] | |
| Mechanical Conversion Annual Failure Rate | [-] | |
| Mechanical Conversion Loads PDF | [N] | |
| Electrical Conversion Rated Power | [kW] | |
| Electrical Conversion Cost | [€] | |
| Electrical Conversion Mass | [kg] | |
| Electrical Mean Transformed Power | [W] | |
| Electrical Transformed Energy | [Wh] | |
| Electrical Conversion Annual Failure Rate | [-] | |
| Grid Conditioning Rated Power | W | |
| Grid Conditioning Cost | [€] | |
| Grid Conditioning Mass | [kg] | |
| Grid Conditioned Mean Active Power | [W] | |
| Grid Conditioned Mean Reactive Power | [VaR] | |
| Grid Conditioned Energy | [Wh] | |
| Grid Conditioning Annual Failure Rate | [-] | |

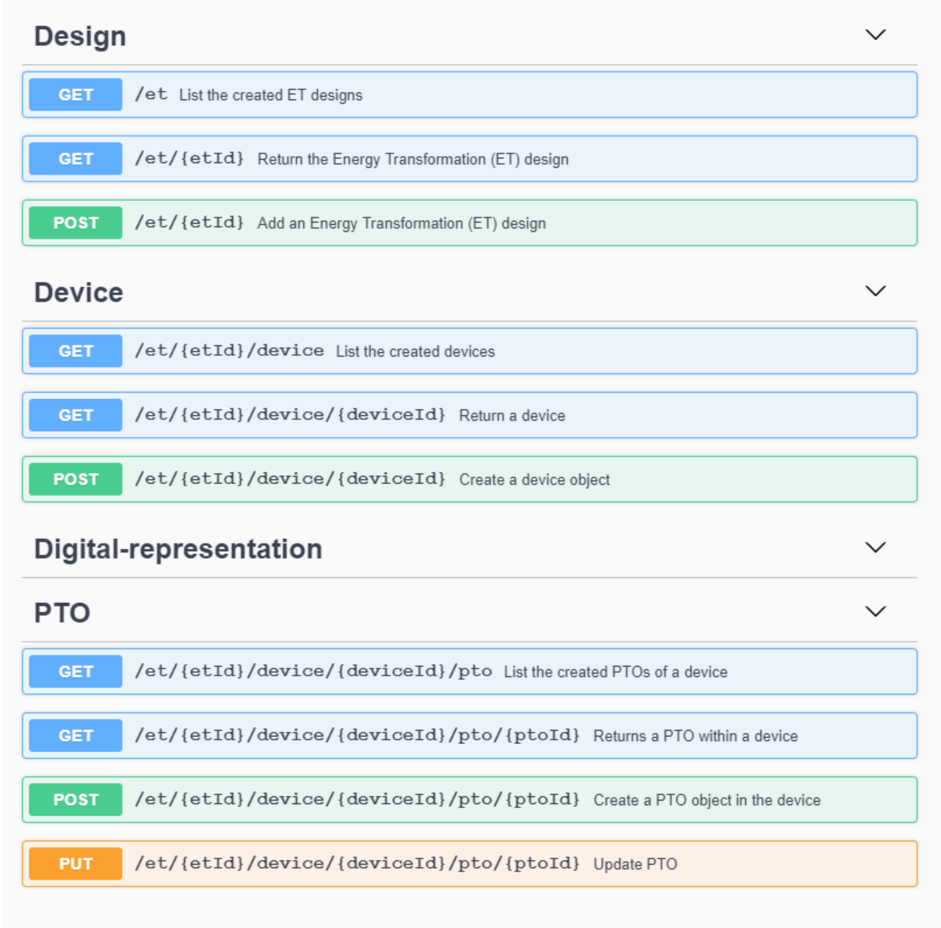
## 3.4 API

The API of the DTOceanPlus software follows a representational state transfer (REST) approach and HyperText Transfer Protocol (HTTP) as the transport protocol. Its robustness is due to strict design principles whose development it has been based on.

The SPEY API follows those principles and indeed the language OpenAPI is adopted. An OpenAPI file was created, in json format, indicating all the paths, the services, and schemas that SPEY will consume, and which will make available for other modules to be consumed.

The backend of the module will receive the services from the other modules, running the Business Logic and then preparing the outputs for the other modules and the users. This will be coded in Python, using Flask Blueprints [38].

The Figure 3.32 shows the general structure of the Energy transformation API:



Design

GET `/et` List the created ET designs

GET `/et/{etId}` Return the Energy Transformation (ET) design

POST `/et/{etId}` Add an Energy Transformation (ET) design

Device

GET `/et/{etId}/device` List the created devices

GET `/et/{etId}/device/{deviceId}` Return a device

POST `/et/{etId}/device/{deviceId}` Create a device object

Digital-representation

PTO

GET `/et/{etId}/device/{deviceId}/pto` List the created PTOs of a device

GET `/et/{etId}/device/{deviceId}/pto/{ptoId}` Returns a PTO within a device

POST `/et/{etId}/device/{deviceId}/pto/{ptoId}` Create a PTO object in the device

PUT `/et/{etId}/device/{deviceId}/pto/{ptoId}` Update PTO

FIGURE 3.32: DTOCEANPLUS ENERGY TRANSFORMATION (ET) API

## 3.5 GUI

The GUI of Energy Transformation module will be included into the main module and as it can be seen Figure 3.33, and consists of two parts. On the left, there are three trees with the three main conversion steps where each transformation steps inputs could be modified

Figure 3.34 to Figure 3.36 show a summary of the initial draft of the graphical user interface of energy transformation, where project inputs, Hydro2Mech, Mech2Elect, Elect2Grid, Control are differenced in different trees.

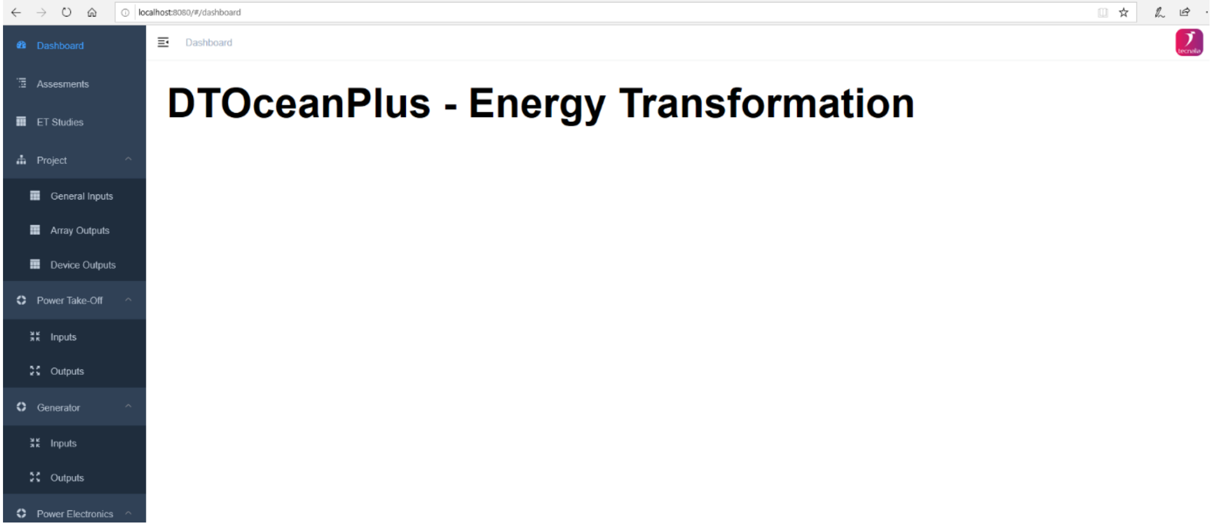
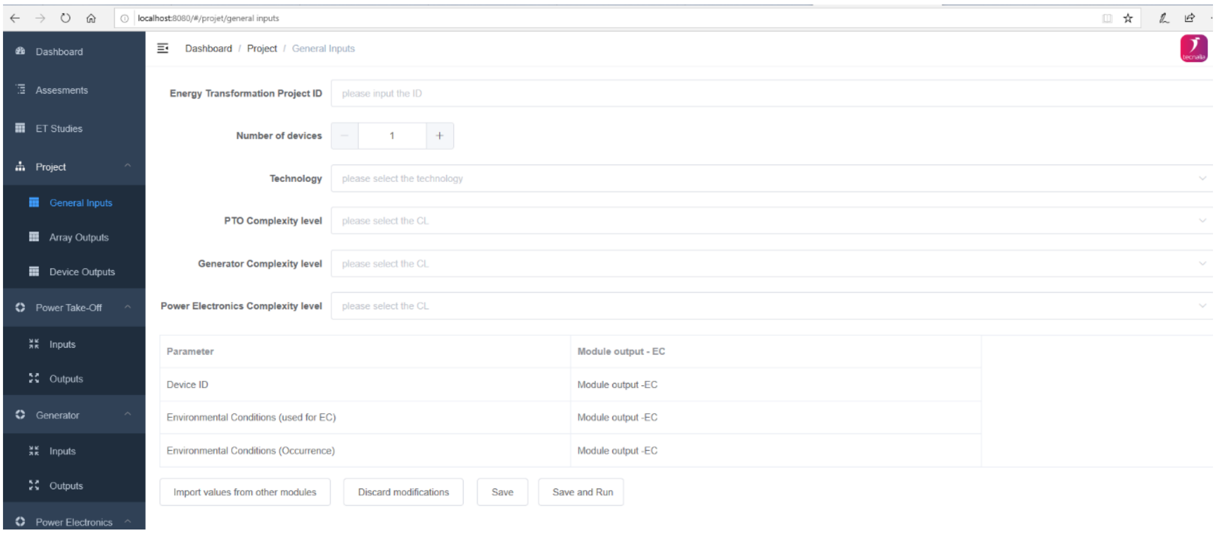


FIGURE 3.33: ENERGY TRANSFORMATION GUI EXAMPLE



**Energy Transformation Project ID** please input the ID

**Number of devices** − 1 +

**Technology** please select the technology

**PTO Complexity level** please select the CL

**Generator Complexity level** please select the CL

**Power Electronics Complexity level** please select the CL

| Parameter | Module output - EC |
|---|---|
| Device ID | Module output -EC |
| Environmental Conditions (used for EC) | Module output -EC |
| Environmental Conditions (Occurrence) | Module output -EC |

FIGURE 3.34: ENERGY TRANSFORMATION GUI EXAMPLE- MECHANICAL TRANSFORMATION INPUTS

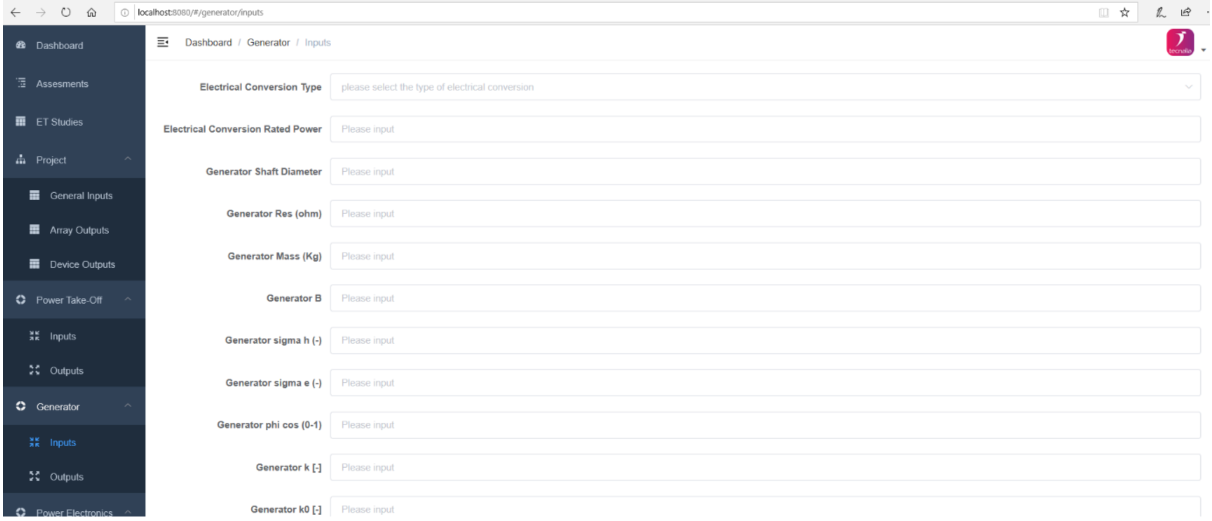


FIGURE 3.35: ENERGY TRANSFORMATION GUI EXAMPLE- ELECTRICAL TRANSFORMATION INPUTS

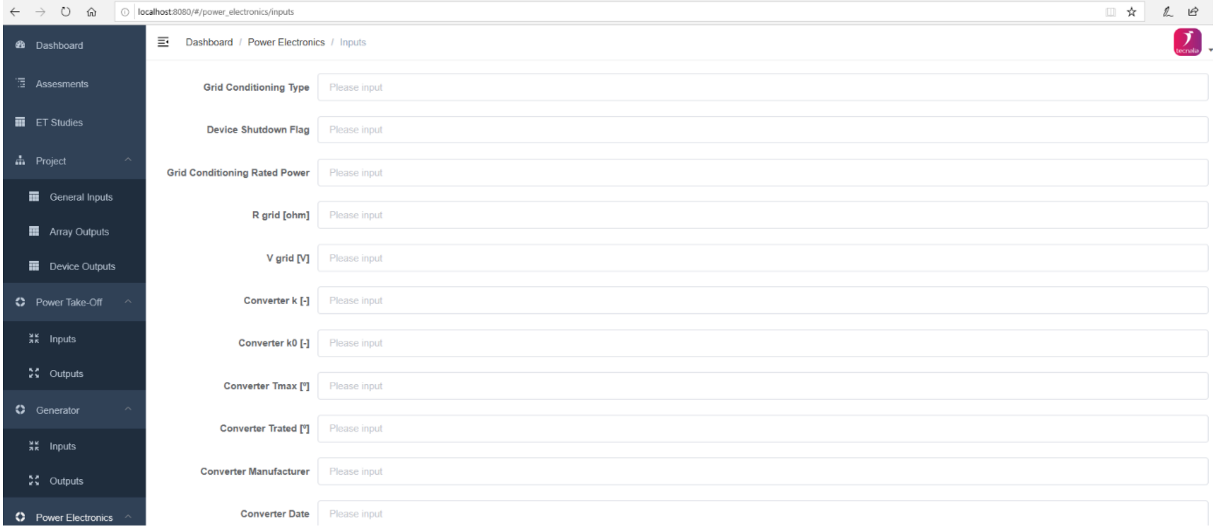


FIGURE 3.36: ENERGY TRANSFORMATION GUI EXAMPLE- GRID CONDICIONING INPUTS

# 4. REQUIREMENTS

The Business Logic and the API of ET have been coded in Python version 3.6. The installation of the module requires the following packages:

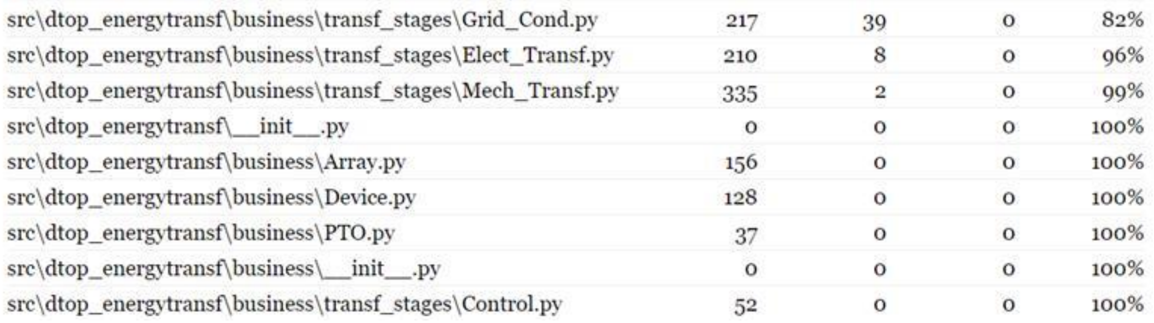
- Numpy
- Matplotlib
- Pandas
- Time
- scipy.stats
- flask

The API has been relying on OpenAPI specification v3.0.2.

The GUI of the module has been developed in Vue.js, using the library Element-UI.

# 5. TESTING AND VERIFICATION

A validation of the input data has been implemented, completing total set of 1135 statements, where different functionalities of the Business Logic have been covered. The unit test coverage of Energy Transformation is high (85%), ensuring the quality and guaranteeing that future developments on the module will be stable.



| | | | | |
|---|---|---|---|---|
| src\dtop_energytransf\business\transf_stages\Grid_Cond.py | 217 | 39 | 0 | 82% |
| src\dtop_energytransf\business\transf_stages\Elect_Transf.py | 210 | 8 | 0 | 96% |
| src\dtop_energytransf\business\transf_stages\Mech_Transf.py | 335 | 2 | 0 | 99% |
| src\dtop_energytransf__init__.py | 0 | 0 | 0 | 100% |
| src\dtop_energytransf\business\Array.py | 156 | 0 | 0 | 100% |
| src\dtop_energytransf\business\Device.py | 128 | 0 | 0 | 100% |
| src\dtop_energytransf\business\PTO.py | 37 | 0 | 0 | 100% |
| src\dtop_energytransf\business__init__.py | 0 | 0 | 0 | 100% |
| src\dtop_energytransf\business\transf_stages\Control.py | 52 | 0 | 0 | 100% |

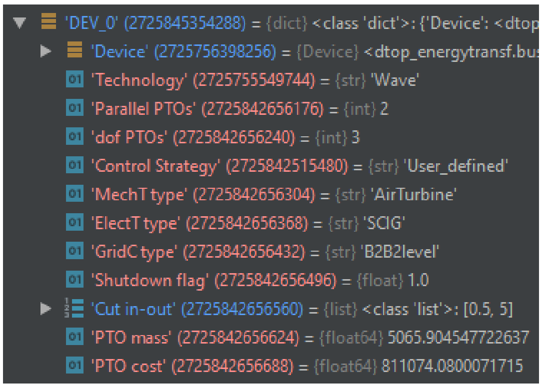
FIGURE 5.1: COVERAGE OF THE TESTING OF THE BUSINESS LOGIC BY MEANS OF UNIT TESTS

# 6. EXAMPLES

The main objective of the energy transformation module is to obtain the following results for the different energy transformation steps:

- Cost
- Environmental issues (mass to obtain Co2 emissions)
- Efficiency
- Reliability

Example of an internal structure at device level is shown in **¡Error! No se encuentra el origen de la referencia.**:



```
▼ 'DEV_0' (2725845354288) = {dict} <class 'dict'>: {'Device': <dtop
  ▶ 'Device' (2725756398256) = {Device} <dtop_energytransf.bus
    'Technology' (2725755549744) = {str} 'Wave'
    'Parallel PTOs' (2725842656176) = {int} 2
    'dof PTOs' (2725842656240) = {int} 3
    'Control Strategy' (2725842515480) = {str} 'User_defined'
    'MechT type' (2725842656304) = {str} 'AirTurbine'
    'ElectT type' (2725842656368) = {str} 'SCIG'
    'GridC type' (2725842656432) = {str} 'B2B2level'
    'Shutdown flag' (2725842656496) = {float} 1.0
  ▶ 'Cut in-out' (2725842656560) = {list} <class 'list'>: [0.5, 5]
    'PTO mass' (2725842656624) = {float64} 5065.904547722637
    'PTO cost' (2725842656688) = {float64} 811074.0800071715
```

FIGURE 6.1: INTERNAL STRUCTURE AT DEVICE LEVEL

The Figure 6.2 shows an example of energy production at the different transformation steps for a single wave energy converter: Hydrodynamic power, mechanic power, electric power, grid integration.

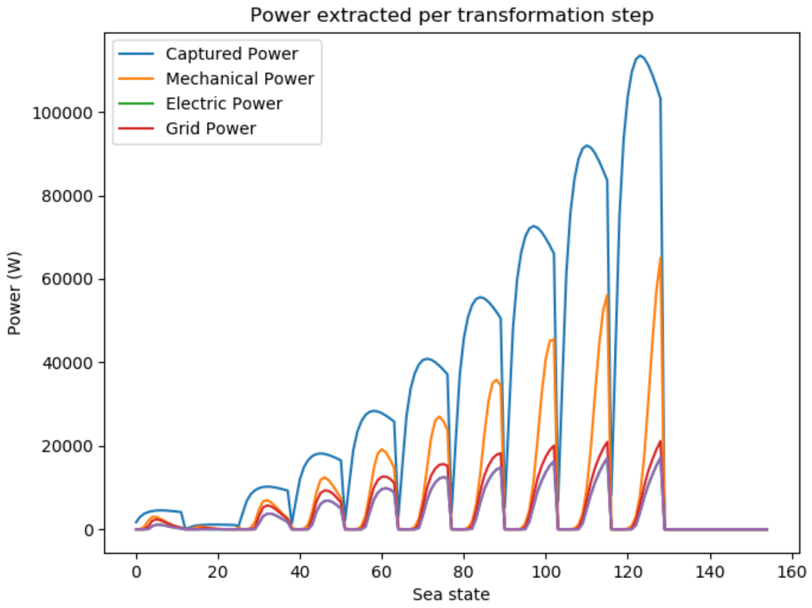


FIGURE 6.2: POWER EXTRACTED PER TRANSFORMATION STEP

Figure 6.3 shows the power production an array of 5 wave energy converters:

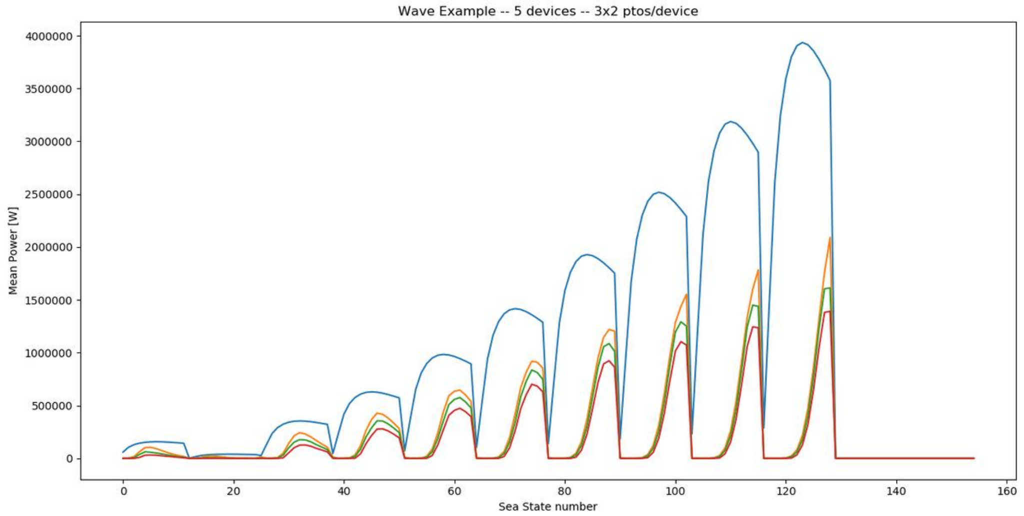


FIGURE 6.3: MEAN POWER FOR TRANSFORMATION STEPS EXAMPLE FOR 5 WAVE ENERGY CONVERTERS: HYDRODINAMIC POWER, MECHANIC POWER, ELECTRIC POWER, GRID INTEGRATION

The Figure 6.4 is an example of power production of an array of 5 tidal devices:

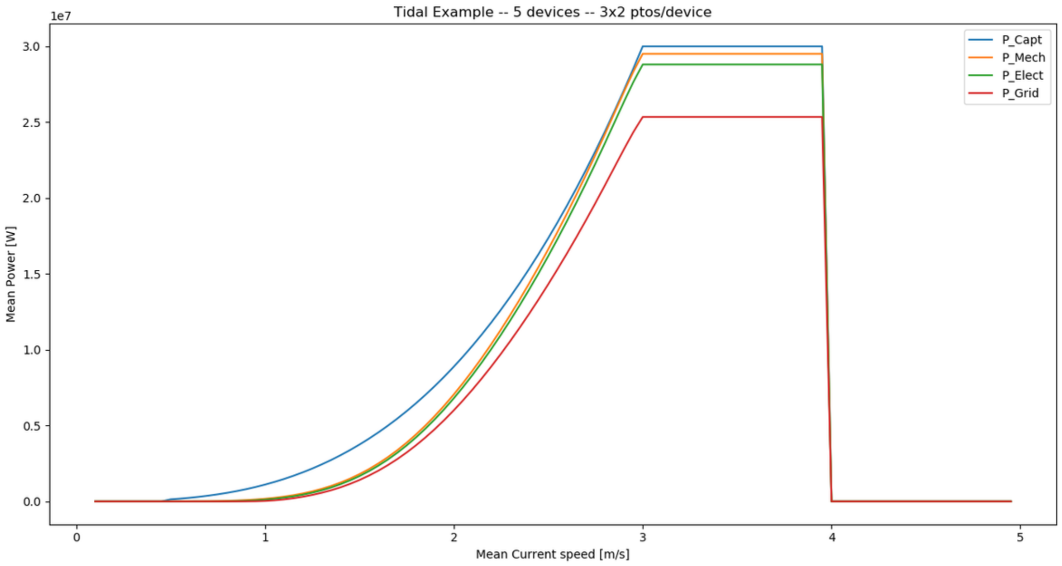


FIGURE 6.4: MEAN POWER FOR TRANSFORMATION STEPS EXAMPLE FOR 5 TIDAL ENERGY CONVERTERS: HYDRODINAMIC POWER, MECHANIC POWER, ELECTRIC POWER, GRID INTEGRATION

# 7. FUTURE WORK

The present deliverable describes the framework and main functionalities of the Energy Transformation (ET) Module, implemented during the tasks T5.2 and T5.5 of DTOceanPlus project. At the time of writing, the module can be run in a standalone mode. However, in order to fully integrate it with the remaining modules of the DTOceanPlus suite of design tools, the following steps are required:

- The OpenAPI file should be "linked" to the other modules and consistent data flow among the different pieces of the tool must be verified.
- The GUI will be developed to be consistent with the other tools and to provide the user with an easy access to the tool and its functionalities.
- Unit test coverage will be improved considering the inputs from the GUI and other modules.
- There will be improvements on the usability and minor additions as a result of the verification and integration activities in the following phase of the project.
- The verification of the module functionality will be carried out to ensure that the tool fulfils the user requirements defined in WP2 and the design guidelines defined in T5.1.

The remaining work is part of the continuous development/integration methodology, as described in Deliverable D7.4 "Handbook of software implementation". These activities will be developed within T5.9 Verification of the code – beta version in order to extend the functionality of the ET module from standalone to fully integrated in the DTOceanPlus toolset.

# 8. REFERENCES

[1] «DTOceanPlus Website», abr. 30, 2020. https://www.dtoceanplus.eu/.

[2] «Noble y Medina-Lopez - DTOceanPlus_D2.1 User consultation UEDIN_2018-08-2.pdf». .

[3] «D5.1_20190416.pdf». .

[4] «Falcão y Gato - 2012 - Air Turbines.pdf». .

[5] A. F. O. Falcão, L. M. C. Gato, y E. P. A. S. Nunes, «A novel radial self-rectifying air turbine for use in wave energy converters. Part 2. Results from model testing», *Renewable Energy*, vol. 53, pp. 159-164, may 2013, doi: 10.1016/j.renene.2012.11.018.

[6] A. F. de O. Falcão y R. J. A. Rodrigues, «Stochastic modelling of OWC wave power plant performance», *Applied Ocean Research*, vol. 24, n.° 2, pp. 59-71, abr. 2002, doi: 10.1016/S0141-1187(02)00022-6.

[7] «DNV-RP-C203: Fatigue Design of Offshore Steel Structures», p. 176, 2011.

[8] A. F. de O. Falcão, «Stochastic modelling in wave power-equipment optimization: maximum energy production versus maximum profit», *Ocean Engineering*, vol. 31, n.° 11-12, pp. 1407-1421, ago. 2004, doi: 10.1016/j.oceaneng.2004.03.004.

[9] R. Islam Rubel, Md. Kamal Uddin, Md. Zahidul Islam, y Md. Rokunuzzaman, «Numerical and Experimental Investigation of Aerodynamics Characteristics of NACA 0015 Aerofoil», *International Journal of Engineering Technologies IJET*, vol. 2, n.° 4, pp. 132-141, abr. 2017, doi: 10.19072/ijet.280499.

[10] A. F. O. Falcão, L. M. C. Gato, y E. P. A. S. Nunes, «A novel radial self-rectifying air turbine for use in wave energy converters», *Renewable Energy*, vol. 50, pp. 289-298, feb. 2013, doi: 10.1016/j.renene.2012.06.050.

[11] «Ricci et al. - 2011 - Control strategies for a wave energy converter con.pdf». .

[12] P. Ricci *et al.*, «Control strategies for a wave energy converter connected to a hydraulic power take-off», *IET Renew. Power Gener.*, vol. 5, n.° 3, p. 234, 2011, doi: 10.1049/iet-rpg.2009.0197.

[13] «PTO System cost metrics.pdf». .

[14] «Wang y Lu - Report on Energy Storage systems.pdf». .

[15] Fritz Faulhaber, «A second look at Gearbox efficiencies», *Machine Design*, p. 2, jun. 2002.

[16] 14:00-17:00, «ISO 281:2007», *ISO*. http://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/81/38102.html (accedido feb. 12, 2020).

[17] «wind-turbine-gearboxes-energiforskrapport-2016-279.pdf». Accedido: feb. 12, 2020. [En línea]. Disponible en: https://energiforskmedia.blob.core.windows.net/media/21270/wind-turbine-gearboxes-energiforskrapport-2016-279.pdf.

[18] «Life modification factor, aSKF». https://www.skf.com/group/products/bearings-units-housings/principles/bearing-selection-process/bearing-size/size-selection-based-on-rating-life/life-modification-factor/index.html (accedido feb. 12, 2020).

[19] «Fricción». https://www.skf.com/es/products/seals/industrial-seals/power-transmission-seals/radial-shaft-seals/friction/index.html?WT.oss=p%C3%A9rdidas&WT.z_oss_boost=0&tabname=Todas&WT.z_oss_rank=7 (accedido oct. 28, 2019).

[20] «ABB_GPCast Iron Motors EN 02_2009.pdf». .

[21] «Catalogue GenPurpMotors_GB_12_2004 RevA.pdf». Accedido: feb. 26, 2020. [En línea]. Disponible en: https://library.e.abb.com/public/367c91cdc1dee017c1257b130057111e/Catalogue%20GenPurpMotors_GB_12_2004%20RevA.pdf.

[22] J. Tamura, «Calculation Method of Losses and Efficiency of Wind Generators», en *Wind Energy Conversion Systems*, S. M. Muyeen, Ed. London: Springer London, 2012, pp. 25-51.

[23] J. Pyrhönen, T. Jokinen, V. Hrabovcová, y H. Niemelä, *Design of rotating electrical machines*, Reprinted. Chichester: Wiley, 2010.
[24] «SELECTION OF electrical steels for magnetic cores.pdf». .
[25] D. Wang y K. Lu, «Report on Energy Storage systems», p. 33.
[26] «ABB Library». https://library.abb.com/ (accedido oct. 28, 2019).
[27] «IMfinity-Catalog_5147b_en.pdf». .
[28] D. Roberts y University of Liverpool, «The application of an induction motor thermal model to motor protection and other functions», 1986.
[29] «EPD AMG France.pdf». .
[30] «EPD for AMS.pdf». Accedido: feb. 26, 2020. [En línea]. Disponible en: https://library.e.abb.com/public/4246fc4b437847fdc1256d63003f681c/EPD%20for%20AMS.pdf.
[31] D. D. Graovac y M. Pürschel, «IGBT Power Losses Calculation Using the Data-Sheet Parameters», p. 17.
[32] ABB, «ABB 5SNE 0800M170100 IGBT module datasheet». .
[33] «Load-cycling capability of HiPak_5SYA 2043-04.pdf». .
[34] «Ciappa - 2002 - Selected failure mechanisms of modern power module.pdf». .
[35] B. Bertsche, *Reliability in Automotive and Mechanical Engineering: Determination of Component and System Reliability*. Berlin Heidelberg: Springer-Verlag, 2008.
[36] «3955AXFR.pdf». .
[37] «010910-ACS 6000 EPD.pdf». .
[38] «DTOceanPlus_D6.2.pdf». .

## CONTACT DETAILS

Mr. Pablo Ruiz-Minguela

Project Coordinator, TECNALIA

www.dtoceanplus.eu

Naval Energies terminated its participation on 31st August 2018 and
EDF terminated its participation on 31st January 2019.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 785921