Scenario Creation Tool

User Guide

Project SEAWEED

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Disclaimer: Any numerical values, graphs or tables in this document are examples only and not to be taken as the opinion of Wave Energy Scotland.

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Contents

1. Getting Excel set up

The Scenario Creation Tool runs on Microsoft Excel[1] and does not need additional files to run. When opening: Click 'Enable Content' if the Security Warning appears:

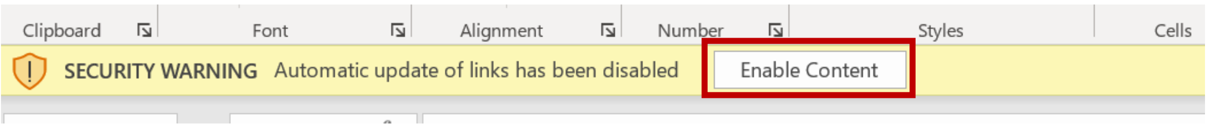


Figure 1 Security warning which may appear when the Scenario Creation Tool is first opened

1) Click 'Update' if this pop-up appears:

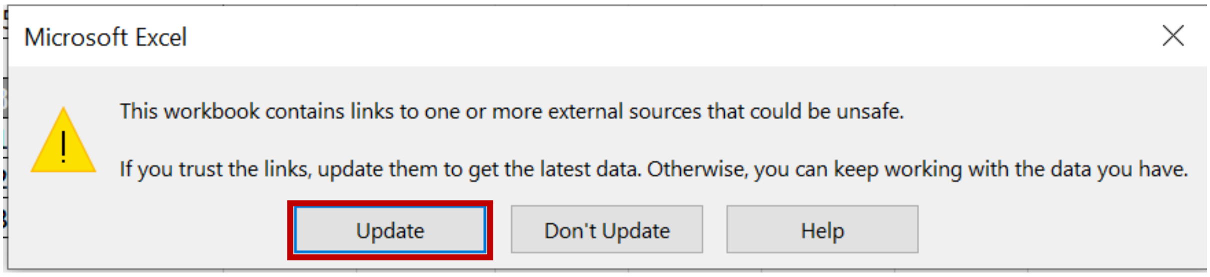


Figure 2 Pop-up which may appear when the Scenario Creation Tool is first opened where the user should select "Update"

2) Ensure that Macros are enabled: Developer > Macro Security > Ensure 'Enable VBA macros (not recommended potentially dangerous code can run) is selected

3) Ensure 'Enable Excel 4.0 macros when VBA macros are enabled' is ticked - See Figure 3.

[1] Version 2108 recommended

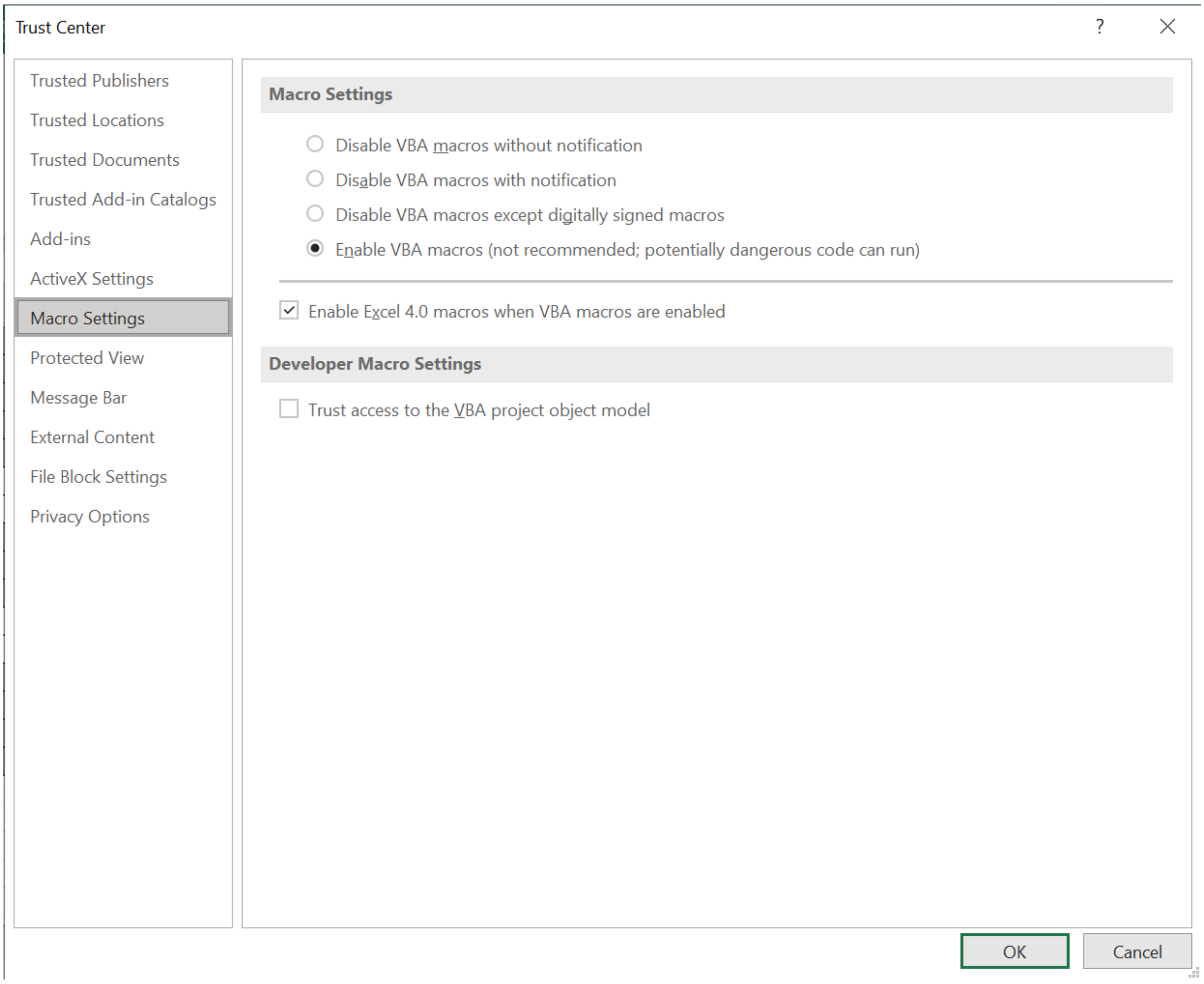


Figure 3 Screenshot of the Developer > Macros Security and the boxes that require to be selected

If steps 1 and 2 are complete, then the tool is ready to use.

2. Introduction

The Scenario Creation Tool provides a structured method for the earliest stages of design in technology development. The core function of the Scenario Creation Tool is to generate and rank scenarios of potential Wave Energy Converter (WEC) attributes and inform the user on the areas of the parameter space that are most likely to yield commercial success.

This techno-economic tool uses a structured innovation approach to identify commercially attractive and technically achievable scenarios, with a scoring system based on their power performance and costs. This is done by leveraging performance and cost data from state-of-the-art wave energy converters and identifying theoretical limits to define thresholds. As a result, a list of scored solutions is obtained depending on resource level, wave energy converter hull shape, size, material, degree of freedom for power extraction, and efficiency.

This Scenario Creation Tool can be used to support private and public investors to inform strategy for future funding calls, and technology developers and researchers in identifying new avenues of innovation.

The power of the tool is the physics, engineering and economics relationships defined which work to provide a ranking for each scenario based on calculated scores for ‘commercial attractiveness’ and ‘technical achievability’. The unique aspect of the tool is that the user can start with a ‘blank piece of paper’, when there is no initial design or concept, and it generates attractive and achievable solutions. This is done within the bounds of existing knowledge, and what is possible within the limitations of the tool. These support the user in proceeding to develop the scenarios into concepts, initial design and on to more detailed design.

The critical part is that using this structured approach from the very beginning of technology development increases the likelihood of success by not being reliant on a stroke of genius or predefined bias about which designs are favourable.

The primary function of the tool is to evaluate many scenarios and provide a ranking based on scores for ‘commercial attractiveness’ and ‘technical achievability’. A scenario is made up of values for input parameters that can be used to describe a wave energy converter (WEC) and its deployment location that are fundamental for calculating the amount of captured energy and the unit cost. These input parameters are treated as completely independent of one another, meaning that scenarios represent potential ‘what-if’ solutions to the wave energy problem.

The commercial attractiveness (CA) score is calculated from the Levelised Cost of Energy (LCOE) of the scenario and comparing it to the user’s Target LCOE. The technical achievability (TA) score assesses the actual achievability of the scenario given current state-of-the-art performance for similar technologies. Once scores are calculated by the tool, scenarios can be filtered out if they are 1) unattractive 2) impossible and 3) unachievable. The methodology is described and discussed in detail in [1].

The first time the tool is opened it will open on the Guidance tab. This tab provides six steps for exploring the tool functionality and covers the three main tabs:

- **Inputs tab**: User inputs to define the scope of the scenarios to be evaluated.
- **Scenarios tab**: A table containing all the generated scenarios and corresponding calculated values.
- **Output_Top10 tab**: Results of top 10 commercially attractive and technically achievable scenarios.

This User Guide covers these tabs in more detail with background information given in the appendices. This user guide also covers the other tabs in the spreadsheet including:

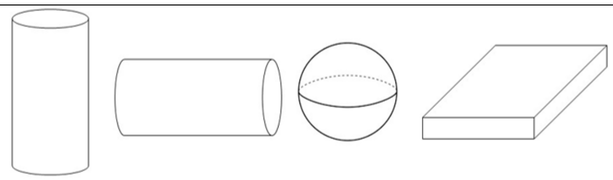
- Assumptions
- Used values
- Lookup tables for Performance and materials.

3. Glossary

The following terms are used in this user guide and the tool and are defined as follows:

Table 1: Glossary of terms uses throughout this User Guide

Scenario	A combination of values for 'Universal parameters' and 'What-If parameters' which together describe the scenario. Thousands of scenarios may be created on each run and then compared to see which are the most commercially attractive and technically achievable.
Universal parameters	These are the values defined in the Inputs tab which apply for all scenarios. They include: Target LCOE (€/MWh), Degree of freedom (heave, surge, pitch etc), Improvement potential (Low, Medium or High), Cost centre breakdowns for Structure, PTO, Moorings, Connection, Installation as a % of CAPEX.
What-If parameters	The what-if parameters are those which can take *any value*, as specified by the user as a set range. They are treated as completely independent from each other. There are no restrictions on the combinations of values which can be assigned. These are: • **Scale (m):** the active device width in the calculation of power production [also defined as the cube root of the total volume]. • **Resource level (kW/m):** the annual average wave power flux available at a site. • **Efficiency (%):** the annual average wave-to-wire efficiency which is the ratio of incident power to produced power. • **CAPEX (€):** the capital expenditure wholly occurring in project year zero. For each of these parameters*, a lower bound, upper bound* and *number of steps* is input by the user into the Ranges table. The corresponding possible values for each parameter are then listed in the Values table below. The maximum number of steps is 10 and these ranges define the scope of scenarios to be explored. Additional what-if parameters (of which a minimum of 1 is chosen for each run) are: • **Materials**: The material (or materials) of interest can be selected from dropdown lists in the Values table. The material options are steel, rubber, Glass Reinforced Plastic (GRP), reinforced concrete and PU nylon. • **Shape**: The shape (or shapes) of interest can be chosen from the dropdown lists in the values table. The shape options are vertical cylinder (Vcylinder), horizontal cylinder (Hcylinder), sphere and cuboid.

	 *Figure 4 The four shape options for the Scenario Creation Tool from left to right are: Vcylinder, Hcylinder, sphere and cuboid.*
Commercial attractiveness	The commercial attractiveness (CA) score is a measure of how close to your Target LCOE in €/MWh the scenario scores. CA score ≥1, the scenario is considered commercially attractive, which is due to the following: the higher the CA score is, the more commercially attractive the scenario is.
Technical achievability	The technical achievability (TA) score is a measure of how achievable the scenario is. This includes how far from the current State of the Art the scenario is in terms of both power and cost [which is also how much 'improvement potential' is possible]. The higher the TA score, the more achievable the scenario is.
Fundamental relationships	The engineering, physics, and economic relationships which drive the earliest stages of assessing the attractiveness of concepts. These relationships between parameters that are assumed to be intrinsic to the wave energy problem. They are used in the tool to calculate LCOE and filter out impossible and unachievable scenarios.
Possible threshold	The threshold that is used to filter the 'impossible'* scenarios from the list, both in terms of power limits, and cost limits e.g. A structure cannot be manufactured for less cost than the raw material cost.
State-of-the-art threshold	The threshold that is used to calculate the technical achievability score and filter the 'unachievable'* scenarios form the list, those that are exceed what has currently been achieved or could be foreseeably achieved by industry (state-of-the-art for wave energy).
Scenario characteristics	The parameters which make up each scenario including both universal parameters and what-if parameters
Filters	Applied thresholds to remove scenarios which exceed defined limits e.g. The 'possible filter' removes scenarios which exceed a possible* threshold in terms of both power and cost, and the 'achievable filter' removes scenarios which exceed a technically achievable* threshold.
Lookup tables	The data behind the CA and TA scores, and the filters. These include tables of power limits for each shape of WEC moving in different degrees of freedom.
***Possible and achievable**	Terms used to describe certain thresholds used in the tool. These are not considered to be actual absolute limits but are defined by certain assumptions and criteria that are described in this document.

4. Guidance Tab

The tool opens on the Guidance tab. This tab provides a summarised step by step guide and the basic information required to run the tool. This information is given in six steps and this is the suggested order of events for exploring the tool functionality.

5. Inputs Tab

In the Inputs tab the user defines the scope of the scenarios to be evaluated when the tool is run, along with several fixed, universal parameters.

5.1. Universal Parameters

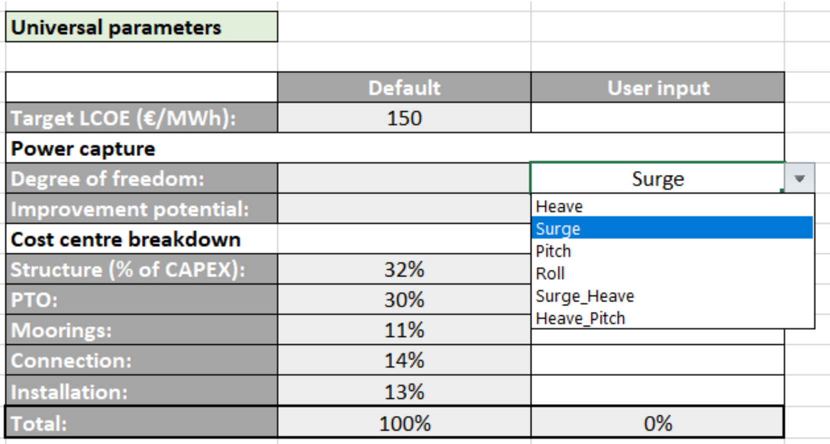
The Universal Parameters are used in the evaluation of the CA and TA score for all the scenarios and are as follows:

Table 2 Definitions of the Universal Parameters used throughout this User Guide

Universal Parameters	Symbol	Units	Definition
Target LCOE	$LCOE_{target}$	€/MWh	A cost-competitive value that can be representative of the chosen market for deployment. Above this value, scenarios are deemed commercially unattractive and can be filtered out (see section 7).
Degrees of freedom (DOF)	-	-	The primary degrees of freedom in which the WEC moves with the incoming wave to extract energy (mode of extraction).
Improvement potential (energy capture)	-	-	Improvement potential for energy extraction. Can be low, medium or high. Used in the calculation of the TA score (see section 6.3.2).
Cost centre breakdown	$C_S, C_P, C_M, C_C, C_I,$	€	The breakdown of five cost centres in terms of percentage of CAPEX. The cost centres are as follows: structure, PTO, moorings, connection and installation.

These are selected/entered in the Universal Parameters table (Figure 5). Default values are listed in the Default column and are used unless a value is input into the User Input column. Options for DOF and improvement potential (low/medium/high) are selected from drop-down lists. Options for DOF are given in

Table 3 and correspond to the data tables in the Lookup_Performance tab (see section 9).



Universal parameters		
	Default	User input
Target LCOE (€/MWh):	150	
Power capture		
Degree of freedom:		Surge
Improvement potential:		
Cost centre breakdown		
Structure (% of CAPEX):	32%	
PTO:	30%	
Moorings:	11%	
Connection:	14%	
Installation:	13%	
Total:	100%	0%

Figure 5: Input of the other main parameters.

*Table 3: Options for DOF that can be selected using dropdown in the Universal parameters table. *Axis of rotation at sea surface.*

DOF options
Surge
Heave
Pitch*
Roll*
Heave and surge
Heave and pitch*

The default values for cost centre breakdown are shown in Figure 6. This breakdown is the average of a selection of real WECs from industry including data from the various WES programmes and is an average across a variety of WEC types. **Note that the tool will use the default values unless the user-input values sum to 100%.** The accompanying pie charts show the used values for cost centre breakdown as percentage of CAPEX and translated to percentage of overall lifetime expenditure.

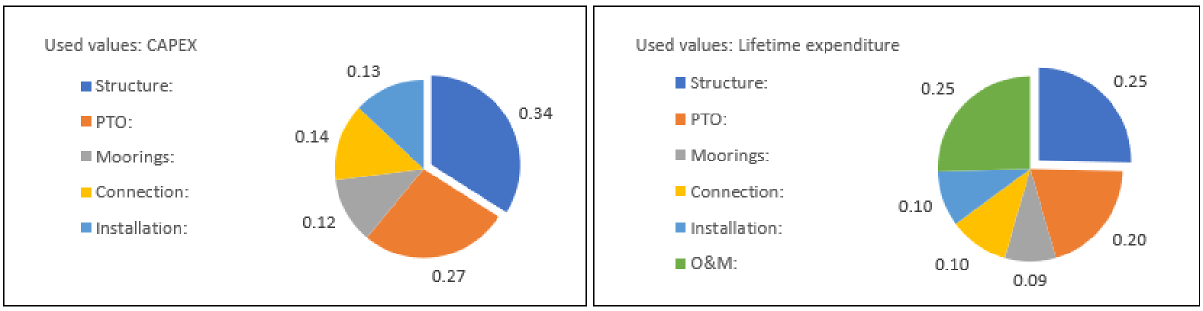


Figure 6: Default breakdowns of CAPEX and corresponding breakdown of lifetime expenditure calculated using the default values for O&M cost, discount rate and project lifetime (see section 8).

5.2. What-If Parameters

Scenarios are defined by a combination of values/options for six What-If Parameters: hull scale, resource level, efficiency, capital expenditure (CAPEX), primary material and hull shape. These parameters are defined as follows:

Table 4 Definitions of What-If parameters used throughout this User Guide

What-If Parameters	Symbol	Units	Definition
▸ Scale	L	m	Referring to the hull only. The active device width in the calculation of power production or the cube root of the total volume.
▸ Resource level	J	kW/m	The annual average wave power flux (kW/m) available at a site.
▸ Efficiency	ε	%	The annual average wave-to-wire efficiency which is the ratio of incident power to produced power.
▸ CAPEX	-	€	The capital expenditure, wholly occurring in project year zero.
▸ Primary material	-	-	The primary structural material of the WEC hull.
▸ Shape	-	-	The shape of the WEC hull which oscillates to capture energy.

The number and range of values/options for each parameter is controlled by the user and the tool evaluates every possible combination.

Firstly, lower bounds, upper bounds and number of steps are entered for the scale, resource level, efficiency and CAPEX parameters in the Ranges table (Figure 7). The corresponding possible values for each parameter are then listed in the Values table below. The maximum number of steps is 10 and these ranges define the scope of scenarios to be explored. For example, the resource level could be explored from 20 - 60kW/m in 6 steps and this would give a step size of 8kW/m.

wave energy SCOTLAND

What if? parameters				
Ranges	**Scale (m)**	**Resource (kW/m)**	**Efficiency (%)**	**CAPEX (£)**
Lower bound:	10	15	50%	800000
Upper bound:	50	75	100%	1000000
Number of steps:	2	2	2	2

Values					
Shape	**Material**	**Scale (m)**	**Resource (kW/m)**	**Efficiency (%)**	**CAPEX (£)**
Barge	Steel	10.00	15.00	50%	800000
HCylinder	GRP	50.00	75.00	100%	1000000
VCylinder		#N/A	#N/A	#N/A	#N/A
	GRP Rubber PU-nylon	#N/A	#N/A	#N/A	#N/A
		#N/A	#N/A	#N/A	#N/A
		#N/A	#N/A	#N/A	#N/A
		#N/A	#N/A	#N/A	#N/A
		#N/A	#N/A	#N/A	#N/A
		#N/A	#N/A	#N/A	#N/A
		#N/A	#N/A	#N/A	#N/A
3	2	2	2	2	2

Figure 7: Input of ranges for what-if parameters and options for primary material and shape.

Secondly, options for primary material and shape are selected using drop down lists in the Values table (Figure 7). Multiple options can be chosen for both material and shape from the lists given in Table 5. The material options correspond to the lookup table in the Material tab and the shape options correspond to the lookup tables in the Performance tab (see section 9).

Table 5: Material and shape options that can be selected from dropdowns in the Values table.

Material options	Shape options
Steel	VCylinder (vertically orientated cylinder)
Reinforced concrete	HCylinder (horizontally orientated cylinder)
Glass reinforced plastic (GRP)	Sphere
Rubber	Cuboid
Polyurethane coated (PU) nylon	

The last action before leaving the Inputs tab is to click the “Generate scenarios and calculate scores” button (Figure 8) before moving on to the Scenarios tab. The total number of scenarios evaluated by the tool is shown above this button and is the number of possible combinations of values in the Values table.

Total number of scenarios:	**32**

Generate scenarios and calculate scores

Figure 8: Pressing this button in the Inputs tab generates and scores the scenarios.

In the example given in Figure 7, there are two options for each of the parameters, meaning there are 32 combinations or scenarios which will be evaluated by the tool.

6. Scenarios Tab

Scenarios are generated by pressing the 'Generate scenarios and calculate scores' button on the Inputs tab (Figure 8). This creates a table containing all the scenarios in the Scenarios tab.

Calculated and corresponding values for each scenario are provided in a columnar format in the table, including the CA and TA scores and threshold values used to filter out impossible and unachievable scenarios. This tab is provided to give visibility of the various calculation steps, and to show which scenarios do not meet the criteria of the filters outlined in section 6.4.

Table 6: Colour coding of columns in Scenarios tab.

Colour code	Example	Column type	Description
Yellow	Scale (m)	What-If parameters.	Input by user, define the scenarios.
Blue	Volume (m^3)	Scenario characteristics.	Calculated from user inputs and default values.
Purple	SOA efficiency (-)	Threshold values.	Corresponding to scenario, calculated from lookup tables.
Green	CA score (-)	Scenario scores.	Calculated from scenario characteristics and threshold values.
Orange	Attractive (?)	Filters.	True/false based on thresholds and scores.

6.1. Scenario Characteristics

The scenario characteristics are calculated from the What-If Parameters, Universal Parameters and other assumptions listed in the Assumption tab (see section 8). The following sections describe each column from left to right.

6.1.1. Availability

A value for availability, corresponding to the resource level, is selected from a lookup table labelled 'Availability' in the Assumption tab. Linear interpolation is used if the value of resource level is between those in the table.

The relationship between availability and resource level used by the tool is described in appendix A. It was created by finding the relationship between resource level and accessibility and then relating this to availability based on values given in the literature.

6.1.2. Shape Key

The shape key is the number of the lookup table in the Used Values tab that relates to the possible average power values of each shape.

6.1.3. Volume

In the current iteration of the tool the outer WEC volume is assumed simply to be the cube of the scenario scale parameter for all shape cases:

$$V_{\text{out}} = L^3$$

This assumption is under review with the intention to link active width and volume differently for different shapes of hull, as is seen in Figure 4 .

6.1.4. Material Key

The material key is the row number of the Materials lookup table corresponding to the material of the scenario.

6.1.5. Material Mass

A linear relationship is then used to calculate the mass of primary structural material from the outer volume:

$$M_{\text{mat}} = \kappa \cdot V_{\text{out}} \quad [\text{t}]$$

Where κ is a constant in [t/m^3] that represents the overall density of the WEC and which is characteristic of material type, as given in Table 12. The value of κ for steel was found through the analysis of existing or modelled WECs (Appendix D). The values used for κ for each of the material options are given in section 9.2 and the basis for these values is outlined in Appendix E.

It should be noted that this relationship does not include the ballast required to keep the WEC in floating equilibrium.

6.1.6. Average Power

The average power produced by the WEC in each scenario, $\overline{P}$, is assumed to be the product of the scale (active width), efficiency (annual average efficiency) and resource level (annual average incident energy per meter of wave crest), as according to the formula:

$$\overline{P} = L \cdot \varepsilon \cdot J \quad [\text{kW}]$$

where L is the scale parameter, J is the resource level parameter, and ε is the efficiency parameter, all as defined in Section 5.2. The average power value is multiplied by the availability (A) and the number of hours in the year to give Annual Energy Production (AEP):

$$\text{AEP} = \overline{P} \cdot A \cdot \text{hours}_{\text{year}} \quad [\text{kWh}]$$

The value of availability corresponding to the scenario is calculated from a lookup table (section 6.1.1) and the average number of hours in a year is taken as 8766 [2].

This method for estimating AEP is considered reasonably accurate (+/- 50%) [3]. It should be noted that, because annual average values are used, this analysis cannot be used to indicate the variability in wave climate between locations and how different designs of WEC may be suited to certain locations over others even if they have the same resource level.

6.1.7. Rated Power

The assumed value of capacity factor (c_f) represents the ratio of the average produced power ($\overline{P}$) to the rated power of the WEC (P_{WEC}). Therefore, the scenario rated power is calculated using the formula:

$$P_{\text{WEC}} = \frac{\overline{P}}{c_f} \quad [\text{kW}]$$

The rated power value is used to check that the costs assigned to the cost centres (other than structure) are feasible.

Note that a fixed value of the capacity factor is used for every scenario. The optimum capacity factor (or rated power value) in terms of both lowest cost and maximum energy capture is dependent on several factors including the wave climate, WEC hydrodynamics and the above-rated operating strategy – parameters that are beyond the scope of the analysis performed in the tool.

6.1.8. LCOE

LCOE is calculated for each scenario using the formula:

$$\text{LCOE}_{\text{scenario}} = \frac{\text{PV(EXP)}}{\text{PV(EP)}} = \frac{\text{CAPEX+PV(OPEX)}}{\text{PV(EP)}} \quad [\text{€/kWh}]$$

Where PV indicates the present value, EXP is the lifetime expenditure, EP is the lifetime energy production and OPEX is the lifetime operational expenditure. CAPEX is assumed to occur solely in year 0 and, therefore, does not need to be adjusted to the present value.

A multiplication factor, τ, is used to calculate present value, for example, where PV(EP) = AEP $\cdot\ \tau$. A value for τ is selected from a lookup table (Table 7) with three options for both discount rate and project lifetime.

The default values of discount rate and project lifetime are 0.10 and 20 years respectively, and this results in a default ratio of CAPEX to total lifetime expenditure of 76% (Figure 6).

Table 7: Multiplication factor used to calculate present value according to project lifetime and discount rate. Bold indicates default values.

$\boldsymbol{\tau}$	$r = 0.05$	$\boldsymbol{r = 0.10}$	$r = 0.15$
$t_{\text{life}} = 15$ yrs	10.38	7.61	5.85
$\boldsymbol{t_{\text{life}} = 20}$ yrs	12.46	**8.51**	6.26
$t_{\text{life}} = 25$ yrs	14.09	9.08	6.46

6.1.9. Cost Centres

For each scenario the absolute value assigned to each cost centre is taken as a percentage of the what-if CAPEX according to the cost centre breakdown defined in the Inputs tab. For example, the structure cost, S, is calculated according to the formula:

$$\text{S} = \text{CAPEX} \cdot s \quad [€]$$

Where s is the proportion of CAPEX that is associated to the primary structure.

Similarly, the annual OPEX value is calculated according to the formula:

$$\text{OPEX}_{\text{year}} = \%\text{OPEX} \cdot \text{CAPEX} \quad [\,€/\text{a}\,]$$

The lifetime OPEX corrected to its present value is then $\text{PV}(\text{OPEX}) = \text{OPEX}_{\text{year}} \cdot \tau$.

The values in the cost centre columns are highlighted in red if they are below certain minimum cost centre thresholds and are, thus, likely to be unfeasible. This is explained further in section 6.5.

6.2. Threshold Values

The threshold values are selected or interpolated from tables in the Lookup tabs based on the value of the What-if parameters. These are the maximum and state-of-the-art (SOA) values for the annual average power produced by a WEC and the minimum and SOA values for the hull structure cost.

It should be noted that the ‘possible’ values are not considered to be actual absolute limits but are defined by certain assumptions and criteria given in this document.

6.2.1. Possible Power

The possible power value ($\overline{P}_{\max}$) is taken as a maximum for annual average power in each scenario. Relationships between the maximum values for annual mean produced power and hull volume were generated using a wave energy converter design optimisation model. The model is capable of finding the optimal shapes that result in the highest mean annual power values with the lowest possible submerged volume. The result of this analysis is a set of values describing the relationship between mean annual power and submerged volume depending on hull shape, DOF and resource level. For the purpose of describing maximum mean power absorption, as considered in the Budal upper bound, the submerged volume is a determining factor. This also defines the dimensions of the device. For this reason, in the optimisation process, submerged volume is the metric chosen to represent device size. A short summary of the model methodology, as developed to generate the fundamental relationships, is provided in Appendix B and further detail can be found in [4]. This threshold is used to determine the outcome of the possible filter. In the tool, the value of $\overline{P}_{\text{max}}$ is dependent on scale, resource level, DOF and shape. For each scenario, it is calculated using interpolation of the table in the Lookup_Performance tab that matches the DOF and shape. A fuller description of the data is given in section 9.

6.2.2. SOA Power

The SOA power value ($\overline{P}_{\text{SOA}}$) is taken as the SOA for annual average power in each scenario. It is used in the calculation of the TA score and to determine whether a scenario is 'achievable'. The evaluation of the SOA threshold is more generalised than for the possible value, owing to limited availability of source data. In the tool, the value of $\overline{P}_{\text{SOA}}$ is dependent on scale and resource level only. For each scenario, it is calculated using interpolation from the table in the Lookup_Performance tab which is used for degrees of freedom and for all shapes. The SOA power lookup table comes from analysis of power matrices of real (or realistic models of) WECs. A fuller description of these data is given in section 7.

6.2.3. Minimum Structure Cost

The minimum structure cost (S_{min}) value is calculated using the formula:

$$S_{\text{min}} = c_{\text{raw}} \cdot M_{\text{mat}}$$

Where c_{raw} is the is the raw cost of the material (€/t) and M_{mat} is the mass of the primary material required for the main WEC structure (t). The value of M_{mat} is calculated using the relationship given in section 6.1.5 which uses total WEC volume and a material dependent total density. Values for c_{raw} are also material dependent and are accessed by the tool from the Materials table in the Loookup_Materials tab. Note that ballast is assumed to be zero cost.

6.2.4. SOA Structure Cost

The SOA structure cost (S_{SOA}) values is calculated using the formula:

$$S_{\text{SOA}} = c_{\text{fab}} \cdot M_{\text{mat}}$$

Where c_{fab} is the is fabricated cost of the material (€/t) and M_{mat} is the mass of the primary material required for the main WEC structure (t). The value of M_{mat} is calculated using the relationship given in section 6.1.5 which uses total WEC volume and a material dependent total density. Values for c_{fab} are also material dependent and are accessed by the tool from the Materials table in the Loookup_Materials tab. Note that ballast is assumed to be zero cost.

6.3. Scores

Each scenario is scored for its 'commercial attractiveness' and 'technical achievability'.

6.3.1. Commercial Attractiveness Score

The CA score is calculated as follows:

$$\text{CA} = \frac{\text{LCOE}_{\text{target}}}{\text{LCOE}_{\text{scenario}}}$$

Where $\text{LCOE}_{\text{scenario}}$ is the LCOE estimated for the scenario and $\text{LCOE}_{\text{target}}$ is the target value of LCOE input by the user. Therefore, **the higher the CA score the more attractive the scenario.**

6.3.2. Technical Achievability Score

The TA score is used to identify the most (and least) achievable scenarios, given current or SOA thresholds for each technology type. There are two components to the TA score calculation: The Power TA score, which indicates the achievability of the scenario average power value ($\bar{P}$) in comparison to the SOA, and the Cost TA score, which indicates the achievability of the scenario structure cost value (C_{S}) in comparison to the SOA.

The two components are calculated using the following formula:

- The power TA score (TA_P) is calculated using the following equation:

$$\text{TA}_P = \left(\frac{\bar{P}_{\text{max}} - \bar{P}}{\bar{P}_{\text{max}} - \bar{P}_{\text{SOTA}}}\right) \cdot \beta_P$$

Where $\bar{P}_{\text{max}}$ is the maximum annual mean produced power, $\bar{P}\bar{P}$ is the scenario average power value, $\bar{P}_{\text{SOA}}$ is the SOA power and β_P is a power improvement potential factor.

- The cost TA score (TA_{c}) is calculated using the following equation:

$$\text{TA}_{\text{c}} = (\frac{S - S_{\min}}{S_{\text{SOA}} - S_{\min}}) \cdot \beta_C$$

Where β_C is the improvement potential factor for the scenario material option (as given in the materials lookup table, see section 9.2).

The two scores are added together to give the combined TA score. **The higher the TA score the better and more achievable a scenario.**

The improvement potential factor acts as a weighting to account for the differences in feasibility of improvement for the different technology types. Three values of β are used, corresponding to low, medium and high improvement potential (Table 8). This characterisation of technologies is outlined further in Appendix E.

Table 8: Improvement potential levels.

Improvement potential	β
Low	1
Medium	2
High	3

6.4. Filters

Filters are used to determine whether the combination of values for each scenario is:

- attractive
- possible
- achievable

For each of these filters, a scenario is either TRUE (does not exceed the threshold) or FALSE (exceeds the threshold), as indicated in the filter columns in the Scenarios tab. To understand the severity of these filters on the scenarios, TRUE or FALSE can be selected in each table column using the built-in excel functionality. Alternatively, a summary is given in the Outputs_Top10 tab. A "reset filters" button is provided to the far right of the Scenarios table which unsorts all the table columns.

It should be noted that the 'possible' and 'achievable' thresholds are not considered to be actual absolute limits but are defined by certain assumptions and criteria given in this document.

6.4.1. Possible Filter

The possible filter is used to filter out impossible scenarios, those that exceed the maximum threshold for power ($\bar{P} > \bar{P}_{\text{max}}$), those that exceed the minimum threshold for cost of the structure ($S < S_{\text{min}}$), and those that exceed both.

6.4.2. Attractive Filter

The attractiveness filter is used to filter out unattractive scenarios with a score of CA < 1. This indicates that they do not meet the target value of LCOE that can be changed on the Inputs tab.

6.4.3. Achievable Filter

The achievable filter is used to filter out scenarios that exceed the SOA threshold of power ($\bar{P} > \bar{P}_{\text{SOA}}$), those that exceed the SOA threshold for cost of the structure (S$<$ S_{SOA}), and those that exceed both. According to these criteria, remaining scenarios may be currently possible with available technology and without needing significant improvement. On the other hand, currently available technology would need improvement to provide the scenarios that are filtered out.

6.5. Minimum Cost Centre Check

The final column of the Scenarios table is a check of whether each scenario exceeds a set of minimum thresholds for the costs of each of the cost centres other than the structure (PTO, moorings, connection, installation and OPEX). The value for each scenario can either be TRUE, if it does not exceed the minimum thresholds or FALSE, if it exceeds the minimum thresholds.

This is used to highlight possibly implausible CAPEX values that are not filtered out by the Possible filter (which is based on the structure cost only). For example, very small scales would have a lower filter for structural cost, meaning low CAPEX values would at first appear possible, but are unfeasible in terms of cost centres which do not scale in the same way.

In addition to this column, the absolute values given in the cost centre columns (see section 6.1.9) are highlighted in red if they exceed the minimum thresholds. **If all or most of the scenarios have cost centres highlighted in red, then the ranges of What-if values specified in the Inputs tab should be reviewed.**

Table 9 provides the default values of these minima, given in cost per kW (of rated power). They are found in the Assumptions Tab. The default values are based on the default breakdown of cost centres and costs quoted by developers across the WES funding programmes.

It should also be noted that the default values are valid for more conventional WEC designs. Unconventional WEC designs, such as those that do not conform to the cost centres used in the tool, may not be feasible in these instances. The cost minima for each cost centre are stored in the Assumptions Tab where they can be updated.

Table 9: Minimum cost thresholds for each cost centre– found in the Assumptions Tab (section 8)

Cost centre minima		
PTO vs. rating	600	€/kW
Mooring vs. rating	218	€/kW
Connection vs. rating	286	€/kW
Installation vs. rating	259	€/kW
OPEX vs. rating	75	€/kW/a

These values are advisory and apply to devices of 100kW or larger. For lower rated devices, of less than 100kW these values are not likely to be representative.

7. Output_Top10 Tab

The Output_Top10 Tab is used to display the top 10 scenarios from the Scenarios tab according to their CA score. The top 10 table (see Figure 9) is populated by pressing the “Update filters and get top 10” button (see Figure 10).

			Scores				Check
source (kW/m)	Av. efficiency (-)	CAPEX (£)	CA score	Power TA score	Cost TA score	TA score (combined)	Meets minimums?
75	0.70	5000000	3.00	0.90	0.02	0.92	FALSE
75	0.30	5000000	1.28	2.10	0.02	2.12	FALSE
75	0.70	15000000	1.00	0.90	0.06	0.96	FALSE
15	0.70	5000000	0.82	0.65	0.02	0.67	FALSE
75	0.70	5000000	0.60	0.16	2.43	2.59	FALSE
75	0.30	15000000	0.43	2.10	0.06	2.16	TRUE
15	0.30	5000000	0.35	1.52	0.02	1.54	TRUE
15	0.70	15000000	0.27	0.65	0.06	0.71	TRUE
75	0.30	5000000	0.26	0.37	2.43	2.80	TRUE
75	0.70	15000000	0.20	0.16	7.30	7.45	TRUE

Figure 9: Top 10 table showing the top 10 scenarios by CA score and according to chosen filtering level (in this case no filters).

The Top 10 table provides a summary of the top scenarios, namely, the value of the What-if parameters, the CA and TA scores and a column which indicates whether the cost centre minima have been exceeded (TRUE = cost centres are feasible and above minimum thresholds).

The first time this tab is accessed after generating new scenarios, the scenarios will be unfiltered and the Top 10 table may be populated with CA scores that are unfeasibly high (and consequently TA scores that are very low).

Filters are used to reduce the scenarios listed in the table to those that are of interest. There are five filter levels to choose from in the Filters table (Figure 10). These correspond to combinations of three filters: Attractive, Possible and Achievable. The criteria of these filters are outlined in section 6.4.

Filters	No. of scenarios	As % of total	User control
No filters	200000	100%	◉
Attractive?:	142600	71%	○
Attractive & possible?:	10402	5%	○
Attractive & achievable?:	68	0%	○

Update filters and get top 10

Figure 10: Filters can be applied by choosing a filtering level in the 'User control' column of the Filters table.

The number of scenarios that meet each of these filter levels is also given in the Filters table. If this number is below ten then the Top 10 table will only show those scenarios that have not been filtered out. If this number is zero, then the Top 10 table will show no scenarios and the Input values to the tool should be reviewed.

Minimum and maximum TA scores for all the scenarios are provided in the TA summary table (Figure 11) to display to the user the range of TA scores which were reached.

TA summary			
Power TA score		Cost TA score	
Max. TA score:	3.99	Max. TA score:	39690.15
Min TA score:	-6.92	Min TA score:	-0.39

Figure 11: Minimum and maximum TA scores for all the scenarios.

7.1. Graphs

The results can be viewed on two graphs. The first shows a bar chart of the scenarios listed by their unique Key # and their score for CA and TA, as seen in Figure 12 below.

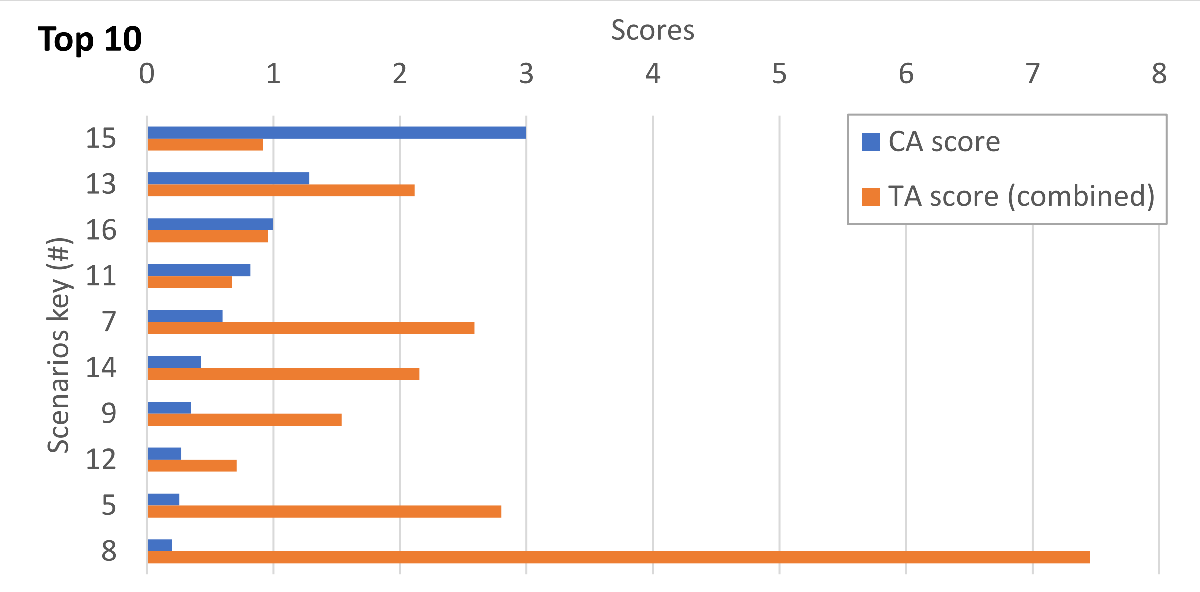


Figure 12 Top 10 most commercially attractive results, displayed as a bar chart with CA and TA scores.

For both TA and CA, the higher score is the most attractive.

The second graph is a scatter plot displaying the top 10 plotted as TA score on the y-axis and CA score on the x-axis, as seen in Figure 13 below.

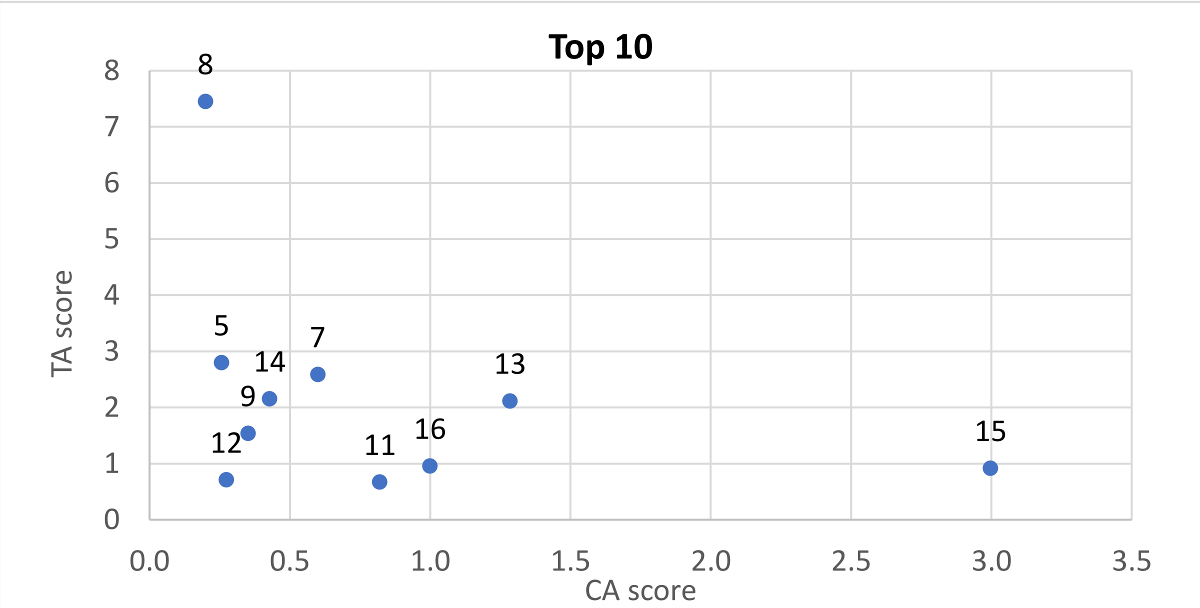


Figure 13: Top 10 most commercially attractive results, displayed as a scatter plot showing CA and TA scores.

The numbers accompanying the points on the scatter plot are the unique key values for the scenarios.

From the graph it can be seen that the scenarios which are the most commercially attractive and achievable appear on the top right-hand corner, whereas the scenarios which are the least commercially attractive and achievable from the top 10 results appear on the bottom left corner.

8. Assumptions Tab

The Assumptions Tab lists parameters that are used in the calculation of the columns in the Scenarios table, but which are not considered central to the Scenario Creation analysis. Default values for these parameters are provided. However, these can be changed for the purpose of a sensitivity analysis.

Parameters in the Assumption table are annual OPEX rate (as a percentage of CAPEX), project lifetime, discount rate and capacity factor. Default values are given in Table 10. The default values for O&M cost, project lifetime and discount rate are widely used in LCOE modelling of wave energy whilst a capacity factor of 30% is the ratio of rated power to average power suggested in [5]. This can be changed by the user of the tool in the 'Assumptions' tab of the Scenario Creation Tool.

Table 10: Default values and other options for the assumed parameters.

Assumed parameter	Default value	Can take…
Annual OPEX rate (%OPEX)	4% of CAPEX	0 to 100%
Capacity factor ($c_f c_f$)	30%	0 to 100%
Project lifetime (t_{life})	20 years	15, 20 or 25 years
Discount rate (r)	0.10	0.05, 0.10 or 0.15[2]

For sensitivity analysis, annual O&M cost and capacity factor can take any value from 0 to 100%. To simplify cashflow evaluation, the project lifetime and discount rate are each restricted to any of three values that are given in a lookup table for the multiplication factor τ, used in the calculation of LCOE (see section 6.1.8).

Also given in the Assumptions Tab is the table of cost centre minima (Table 9), values of β relating to the levels of improvement potential (Table 8), the lookup table for availability versus resource level (Figure 15), and finally, a table of currently used ratios of displaced volume to total volume for each of the hull shapes that can be selected in the tool. The default for this ratio is 50%, however, this can be changed if required.

9. Lookup Table Tabs

The threshold values used to determine the possible and achievable filters, and used to calculate the TA score, are accessed from data stored in lookup tables in two tabs: Lookup_Performance and Lookup_Materials. These data come from a variety of sources, previous work and current analysis.

Interpolation is used where values are needed that are between the datapoints provided in the lookup tables. **Extrapolation is used where values are needed beyond the range of values covered by each table – but it should be noted that this reduces the confidence level.**

[2] Note that the discount rate will vary and the user should make a choice to the best of their knowledge

9.1. Lookup_Performance Tab

The Lookup_Performance tab contains the lookup tables for possible annual average power and SOA annual average power. The computation of the data for these tables is described in Appendix B and Appendix C respectively.

Figure 14 shows the possible power lookup tables. They contain annual average power for different values of displaced volume. Each table relates to a combination of DOF and shape. They were calculated using a geometry optimisation model with few limitations (other than DOF and shape) and therefore, are representative of a maximum threshold for each combination.

There are three sets of tables: one for low energy resource (15 kW/m), one for medium energy resource (45 kW/m) and one for high energy resource (75 kW/m), relating to the resource data that was input to the geometry optimisation model.

Possible average power by shape and DOF

Resource level (kW/m):	15			
1	2	3	4	5
Cuboid-Surge	Displaced		Cuboid-Pitch	Displaced
Mean Annual Power [W]	Volume [m^3]		Mean Annual Power [W]	Volume [m^3]
1178565.9	54218.9		1221577.288	15593.4
1165781.31	46872.20		1215787.679	14383.4
1134624.03	39843.70		1210037.191	14023.8
1126578.16	36884.00		1195193.74	13160.3
1106971.64	34994.70		1191775.861	11507.7
1083837.00	32556.90		1168731.817	10232.2
1057201.10	30823.60		1146769.025	9440.16
1055544.66	27282.30		1127736.219	8441.31
1051225.80	22159.00		1110466.762	8153.84
1003158.82	16246.00		1086717.395	6506.01
986192.84	12498.90		1038933.66	5810.76
882244.72	6270.55		1026805.616	4860.31
840869.29	4804.63		914621.6333	3282.5
734527.73	4371.74		845597.0064	2182.85
615947.75	2703.43		790134.9592	2046.29
535471.00	1975.58		788576.2944	1272.11
478206.91	1782.68		633687.5008	1068.24
411642.20	1606.46		575381.0535	750.489
297476.53	1507.52		451331.2063	570.83
202084.43	641.31		255017.6582	514.764
146754.39	585.76		203227.5027	355.139
65857.31	255.13		21084.55673	156.503

Figure 14: Lookup tables for possible average power versus volume.

Table 11 is the SOA average power lookup table. As it was not possible to find SOA values for each shape and DOF combinations covered by the possible lookup tables, the tool uses an average of WEC types B and D for all shapes and DOF. These are both single-body, oscillating WECs and are considered the most comparable types to those modelled in the geometry optimisation model which produced the possible threshold.

Table 11: Lookup table of SOA average power versus scale.

SOA average power by WEC type						
Resource level (kW/m):	15.00					
Scale (m)	Av. power by WEC type (kW)					
	A	B	C	D	E	Average of B and D
5.00	0.01	2.01	9.75	9.75	33.53	5.88
10.00	0.85	23.94	43.81	43.81	97.92	33.87
15.00	5.47	72.25	85.07	85.07	75.25	78.66
20.00	17.31	138.59	124.63	124.63	42.78	131.61
25.00	37.92	213.57	155.38	155.38	8.46	184.48
30.00	66.30	290.02	175.55	175.55	1.70	232.79
35.00	100.41	359.89	185.78	185.78	0.34	272.83
40.00	138.20	422.76	184.69	184.69	0.00	303.73
45.00	179.20	470.10	180.28	180.28	0.00	325.19
50.00	219.62	516.91	167.70	167.70	0.00	342.31

Interpolation or extrapolation is used in the Scenario Creation Tool to provide the possible and SOA average power threshold values that correspond to the what-if values of scale and resource level in each scenario. The resulting interpolated/extrapolated values are visible in tables in the Used Values Tab.

9.2. Lookup_Materials Tab

Table 12 is the Materials lookup table found in the Lookup_Materials Tab. It contains the characteristics that are used in the calculation of the columns in the Scenarios table, for each material that can be compared in the model.

The parameter κ is an overall density of the WEC hull which is used to relate total volume to material mass. The raw cost per mass and the fabricated cost per mass are then used to find the minimum possible and SOA values of the structure cost, respectively. The values contained within this table are either averages of values found from a range of sources or were calculated using linear interpolation if more data points were available. This process and the sources of data are given in appendices D, E and 0.

A default improvement potential level has been assigned to each material based on the descriptions of improvement potential given in appendix F. This level relates to technical maturity and is used in the calculation of the TA score (see section 6.3.2).

Table 12: Lookup table for characteristics of each material.

Materials key (#)	Materials	κ (kg/m3)	Raw cost: c_{raw} (£/kg)	Fabricated cost: c_{fab} (£/kg)	Mass resource penalty (+% per 5kW/m)	Cost improvement potential
1	Steel	278.76	0.60	2.36		1
2	R. Concrete	528.77	0.11	0.38		1
3	GRP	42.71	2.17	8.54		3
4	Rubber	28.82	1.46	5.74		3
5	PU-nylon	5.13	2.57	10.12		2
6						

A further column in the table is the mass resource penalty. The value entered in this column is the % of additional mass required for every 5 kW/m increase in resource level. It represents the additional mass required for a WEC structure for a site with a higher resource level and harsher wave climate due to survivability considerations. The value of this parameter is considered to be characteristic of material type, but more analysis is required to find sensible values.

10. Used Values Tab

The Used Values Tab is included to simplify certain operations performed by the tool. It summarises some of the parameters that are used in the calculation of the columns in the Scenario table. This includes the parameters with a choice between either default values or user inputted values. It also contains values for the possible and SOA power thresholds, which have been interpolated (or extrapolated) from the performance lookup tables for the input DOF and shape options, and the ranges of scale and resource level. This process of linear interpolation can be understood by examining these tables.

Appendix

A. Availability Versus Resource Level

Treating availability as independent from the resource level is unlikely to provide realistic results. However, including an availability value in the calculation of annual energy production that is resource dependent could be an easy way to model any resource penalty on the final commercial attractiveness score.

Figure 15 is presented in [6] and suggests a relationship between availability and accessibility for, both, a mature technology with improved reliability, and an early technology with initial deployment reliability. The curves are taken from a study which analyses offshore wind.

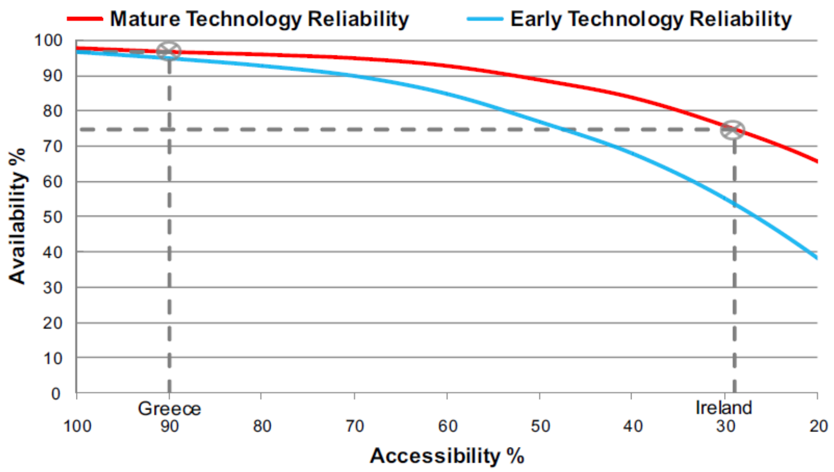


Figure 15: Relationship between availability and accessibility from [6].

The relationship between accessibility, defined as the % of a year when sea conditions are within vessel operating limits, and the site power level ($\bar{J}$) is dependent on the location as well as the operating limits. The operating limits are most simply defined by a maximum significant wave height, for which 2m is typical [7].

The relationship between accessibility and site power level for a 2m maximum was modelled in previous work [8] and is given in Figure 16. This work used hourly sea state data from 50 reference sites distributed across six zones of Ocean in Europe (A to F) shown in Figure 17.

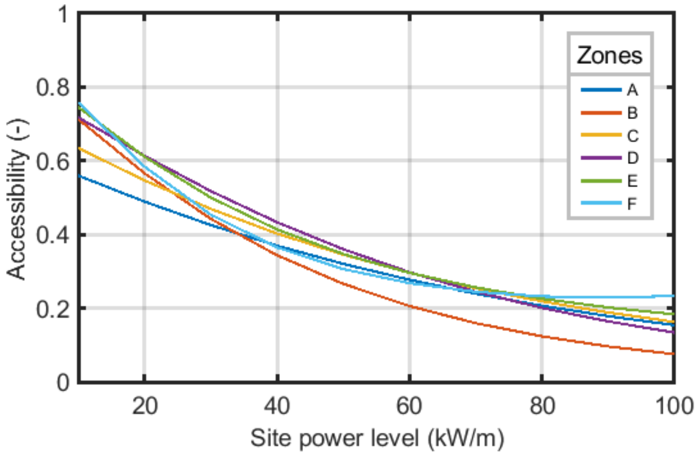


Figure 16: Relationship between accessibility and resource level from [8].

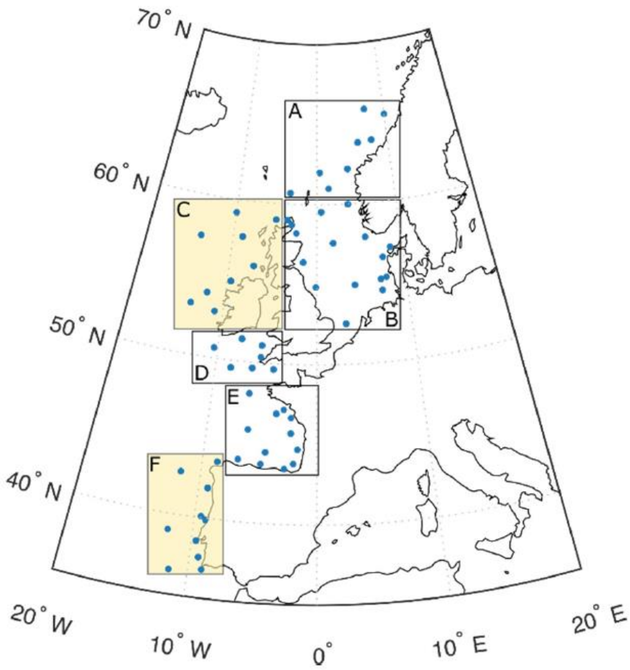


Figure 17: Resource zones from [8].

These two relationships can be combined to provide a relationship between availability and resource level. For example, for zone C (which is off the Irish Coast), a site power level of 60 kW/m gives an accessibility value of around 30% and this equates to an availability value of about 55% for an early technology and 75% for a mature technology.

The Scenario Creation Tool uses this combined relationship (mature technology reliability from Figure 5 and average of the six zones from Figure 16), as shown in Figure 18 which is taken from the Assumption Tab.

Availability									
Resource (kW/m):	3	9	17	27	38	55	81	90	100
Accessability (-):	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.18	0.16
Availability (-):	0.96	0.95	0.93	0.90	0.85	0.77	0.66	0.63	0.61

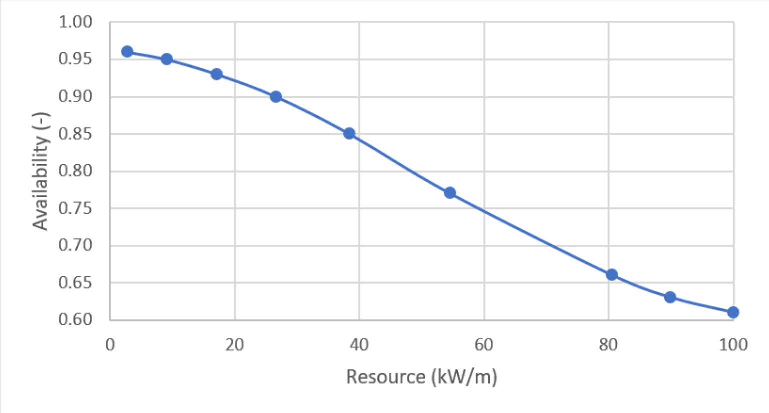


Figure 18: Relationship between availability and resource level used by the tool, found in the Assumption Tab.

B. Possible Power Versus Displaced Volume

The relationships between power and scale used in the Scenario Creation Tool were generated based on a series of data provided by a separate design optimisation tool (see [4] for further details).

This data represents the relationship between power and submerged volume and is used for the possible power threshold in the Scenario Creation Tool. The design optimisation tool is capable of finding designs resulting in the best trade-off between mean annual power and submerged volume. That is, the tool is capable of finding the optimal shapes that result in the highest mean annual power values with the lowest possible submerged volume. The result of this analysis is a set of values describing the relationship between mean annual power and submerged volume.

The wave energy converter geometry optimisation tool was developed and described in detail in [9], [10] and [11]. An overview of the optimisation process is provided in Figure 19. Starting from a given geometry definition, a number of geometries of the defined type (e.g. sphere) are randomly generated. They are evaluated based on their mean annual power production ($\bar{P}$) and their submerged volume (V). Within an optimisation process, the metrics used to evaluate the best performing solutions are referred to as “objective functions”. To calculate the objective function values for each geometry, hydrodynamic characteristics, and volume are obtained from the Boundary-Element-Method based software, WAMIT. Regarding the wave climate, different scatter diagrams for different locations are considered, representing low, medium, and high resource locations. Irregular seas are considered by using a Bretschneider spectrum. The mean annual power is then calculated for a given location with a pseudo time-domain model [12], [11]. The optimisation algorithm is then used to select and generate improved shapes, based on the objective function values of each shape. This optimisation process uses a multi-objective meta-heuristic algorithm, the NSGA-II algorithm, due to its proven ability to consistently find good solutions to different multi-objective problems. Based on the most suitable implementation found in [9], [11], the same crossover and mutation operators as in [13] are used. The optimisation is run for 30 iterations, which was established to be sufficient through a convergence study. This methodology applies to single-body floating devices, and for cases when linear wave theory can be applied.

Overview of applicability and main characteristics of the models used to generate the mean annual power vs displaced volume relationship

- Single-body floating devices
- Linear wave theory
- Pseudo-time domain model
- Uni-directional irregular seas represented with a Bretschneider spectrum

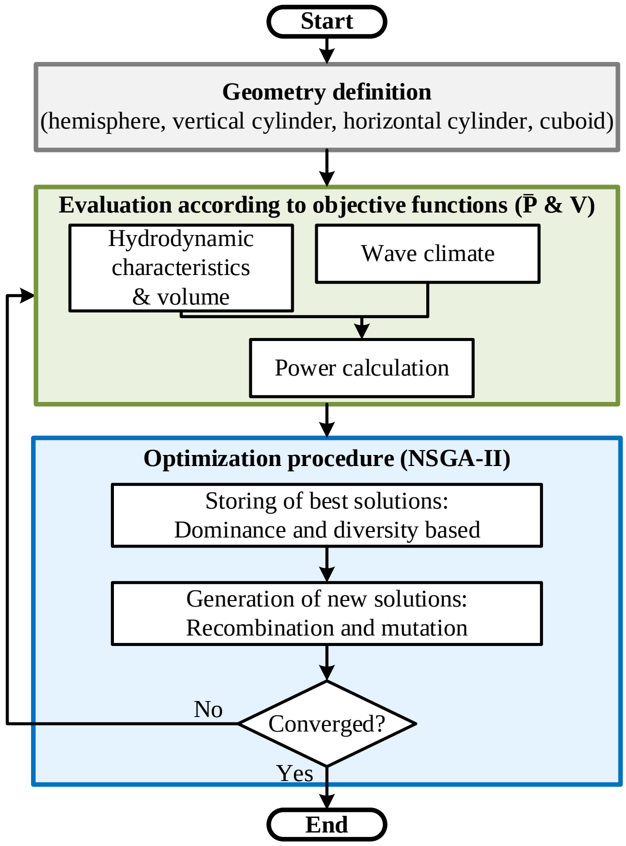


Figure 19: Flow chart representing the design optimisation process [4].

Case studies and assumptions

The case studies modelled with this optimisation tool are summarised in Table 13. All the Degrees-of-Freedom (DoF) and their combinations, as well as all shapes and resource levels, as considered in the Excel-based Scenario Creation Tool are considered here. In the original implementation of the method, PTO stroke and rating constraints could be considered. Since the purpose of these fundamental relationships is to represent the art-of-the possible, no PTO rating constraints were enforced here. In terms of PTO stroke constraints, they were defined following the physical limits as based on [14].

Table 13: Overview of the modelled case studies.

Parameter	Scenario Creation Tool Parameter Type	Case studies
DoF	Universal	Surge, Heave, Pitch, Surge & Heave, Heave & Pitch
Hull shape	What-if	Sphere, vertical cylinder, horizontal cylinder and cuboid
Resource level	What-if	Low (15 kW/m), Medium (45 kW/m) and High (75 kW/m)

The wavelength is used to define some of the aforementioned constraints, and here it is taken as the 95% exceedance probability maximum wavelength for each location, and is therefore referred to as λ_{MAX}. The stroke constraint in surge is based on the fact that a restoring moment is required provided by the wave motion, and so the oscillation cannot exceed more than ¼ of the wavelength λ_{MAX}. For the same reason, the stroke in pitch cannot exceed $\frac{\pi}{2}$. In heave, assuming that the cross-sectional area of the device is constant, then the maximum stroke is defined by the volume of the device, and the waterplane surface area $\left(\frac{V}{2A_w}\right)$. Exceeding this limit would result in the device being outside of the water and therefore linked to slamming, or in the device being fully submerged. Since all devices are assumed to have 50% of their volume submerged[3], for shapes that do not have a constant cross-sectional area, an equivalent approach is to use the draft of the device as the stroke constraint. For this reason, the constraint was adapted to be defined as the geometry's draft (d). The PTO stroke limits used here are summarised in Table 14.

Table 14: PTO stroke limits defined in each Degree-of-Freedom. For more information on the choice of these limits see [1]

	Surge	Heave	Pitch
PTO stroke	$\pm\frac{\lambda_{MAX}}{4}$	$\pm d$	$\pm\frac{\pi}{2}$

[3] The percentage of total volume that is submerged can be changed by the user in the Scenario Creation Tool, which will affect the considered overall volume and structural costs, but it will not be accounted for in the maximum average power calculation. Therefore, the impact of this assumption on the shape itself should be considered by the user when interpreting the results. For example, if it is assumed that the submerged volume is less than 50% of the total volume for a heaving vertical cylinder, then the cylinder might just increase in height and the maximum stroke is not affected. If the submerged volume is assumed to be more than 50% of the total volume, then the height of the cylinder outside of the water may be reduced, and then the stroke constraint would also be reduced. However, it could be assumed that the cylinder has a smaller radius above the free surface so that the stroke constraint still applies and the assumption of the percentage volume is met.

Additionally, limits to the hull geometry had to be defined to avoid the optimisation converging on very large or very small devices. The draft of all shapes was limited to be no larger than 30m. This was defined based on the draft used for the floating offshore wind design in Pelastar [15] where the purpose is to reduce device oscillations, and so should serve as a limit without constraining the range of possible solutions found through the optimisation process. For the width or radius measures again the wavelength was used, so that $\frac{\lambda_{MAX}}{2}$ is used as constraint, to ensure that the evaluated devices can be regarded as point-absorbers.

In the Scenario Creation Tool resource level independent of location is used. For the purpose of generating fundamental relationships, the two locations shown in Figure 17 with the largest difference in range of occurring periods were used and the best results found at the two locations were selected to generate the final fundamental relationships. This was done so that fundamental relationships could be generated independently from location, but dependent on the resource level. The two locations considered for this purpose were zone C located off the coast of Ireland, and zone F located off the coast of Portugal (see Figure 17).

Assumptions and case studies overview

- DoFs: Surge, Heave, Pitch, Surge & Heave, Heave & Pitch
- Hull shapes: Sphere, vertical cylinder, horizontal cylinder and cuboid
- Resource levels: Low (15 kW/m), Medium (45 kW/m) and High (75 kW/m). Two locations (C and F) for each resource level were modelled to find the best trade-off regardless of location.
- PTO rating: No constraint was applied
- PTO stroke: Surge ($\pm \frac{\lambda_{MAX}}{4}$), Heave ($\pm d$), Pitch ($\pm \frac{\pi}{2}$)
- Geometry constraints: Draft (30m), Width and Length ($\frac{\lambda_{MAX}}{2}$)

Example results

The type of fundamental relationships generated with this optimisation tool are shown in Figure 20. The optimisation tool is used to find the best trade-off between mean annual power and submerged volume, and scale is calculated from the submerged volume to be used in the calculation of the Capture Width Ratio.

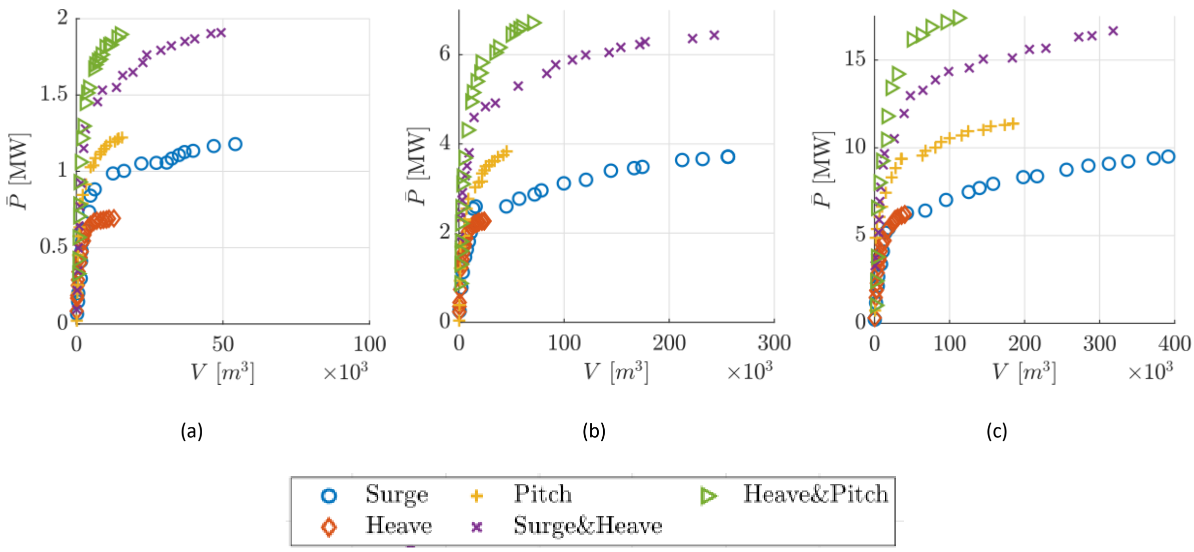


Figure 20: Example fundamental relationships found for a cuboid absorbing power in different modes of motion in (a) low, (b) medium and (c) high resource levels. Note that here $\bar{P}$ refers to the mean annual power, and V to the submerged volume, and the y-axis scales are different between sub plots [1].

C. SOA Power Versus Active Width

To filter out unachievable scenarios and calculate technical achievability a state-of-the-art (SOA) threshold or benchmark for power performance was required. Analysis showed that this threshold was dependent on WEC type (although there were not enough examples of each type in the reference data to generalise), relating to the way in which energy is extracted from the incoming wave.

The method for creating this threshold was to use power matrices for existing/pre-exiting WECs, results from tank testing of scaled prototypes or from realistic numerical models that were based on typical WEC designs. In total 15 power matrices were evaluated.

Average power values were computed for high medium and low resource (15, 45, 75 kW/m annual average power) and in three regions: North Sea, North Atlantic, Mid Atlantic (zones B , C and F , see Figure 17), following the method of combining a power matrix with a sea state occurrence matrix as outlined in [2].

In cases where the performance data was taken from tank testing, more complete power matrices had to be created using interpolation between the representative sea states that were tested (typically data for 12 sea states was provided). Where the power matrices were incomplete, the average power values were interpolated between different sea state bins to provide a more complete estimation of performance. In each of these cases a peak sea state in terms of power performance was either observed or could be interpolated. However, if a device would actually have several peaks in performance then this could not be predicted from the data that was provided.

The aim was then to group each specific WEC into a subset of general types so that each general WEC type could be characterised by average power with scale (and resource). Scaling of power matrices was achieved in different ways for each of the 15 cases. The modelled results from [16] are nondimensionalised with respect to active width (CWR versus non-dimensional period) and so are easily scaled. The power matrices for the other WECs were all scaled using Froude scaling following the method outline in [17].

The differences between different regions/zones needs to be explored further.

D. Steel Mass Versus Total WEC Volume

A fundamental relationship between scale and mass of the primary structural material was required to calculate cost. Easily available information on WEC designs commonly included the outer volume (or displaced volume which was then used to estimate outer volume) along with the mass of steel (structure excluding ballast) and so this relationship was based on the data.

From the 11 datapoints given in [18], [19], [20] and [21], a linear relationship is suggested between the mass of steel (M_{steel} in [t]) and the outer volume (V_{out} in [m^3]), as shown in Figure 21. This can be described by the following formula:

$$M_{\text{steel}} = 0.28 \cdot V_{\text{out}} \pm 268 \quad [\text{t}],$$

where the +/- value is an average of the 95% prediction interval (shown as a dotted line in Figure 21). Another five points were considered outliers, and these are all floating type devices. Three of them are of greater steel mass because they extract energy through a moving body reacting to an extra, relatively stationary, body. Another is a very light device that works similarly but with an internal separately moving mass, and another is a heavy floating oscillating water column which uses a different principle again.

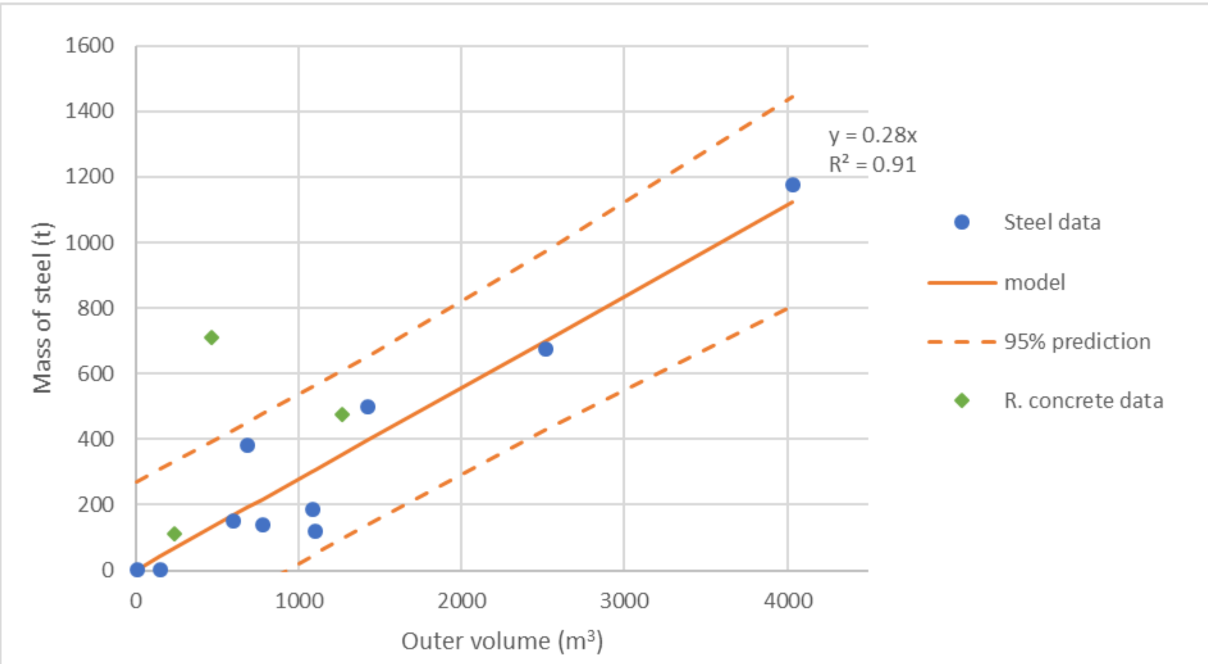


Figure 21: Linear regression of values given in [18], [19], [20] and [21] of steel structure mass (not included ballast) and outer volume of the WEC, with 95% prediction interval

E. Structure Cost Versus Mass of Steel

It is possible to find lots of real examples of steel offshore structures and this includes the vast majority of existing WECs. However, if data is available, values can be given as either cost per kW, cost per mass or cost per surface area and it is not always possible to determine a common characteristic. For cost per mass, a quick search provided data for three types of offshore steel structure:

- Steel WEC structures: 11 datapoints
- Steel ship hulls: 5 datapoints
- Wind turbines (whole turbine including tower): 3 datapoints.

The data for WECs and ships is plotted in Figure 22 and given in [18], [19], [20] and [21]. The cost versus mass trend used by the tool is based on WEC examples and is shown as a solid orange line along with the 95% prediction interval, a zero y-intercept is assumed for simplicity when adjusting for other materials, but a better fit is achieved with a non-zero y-intercept:

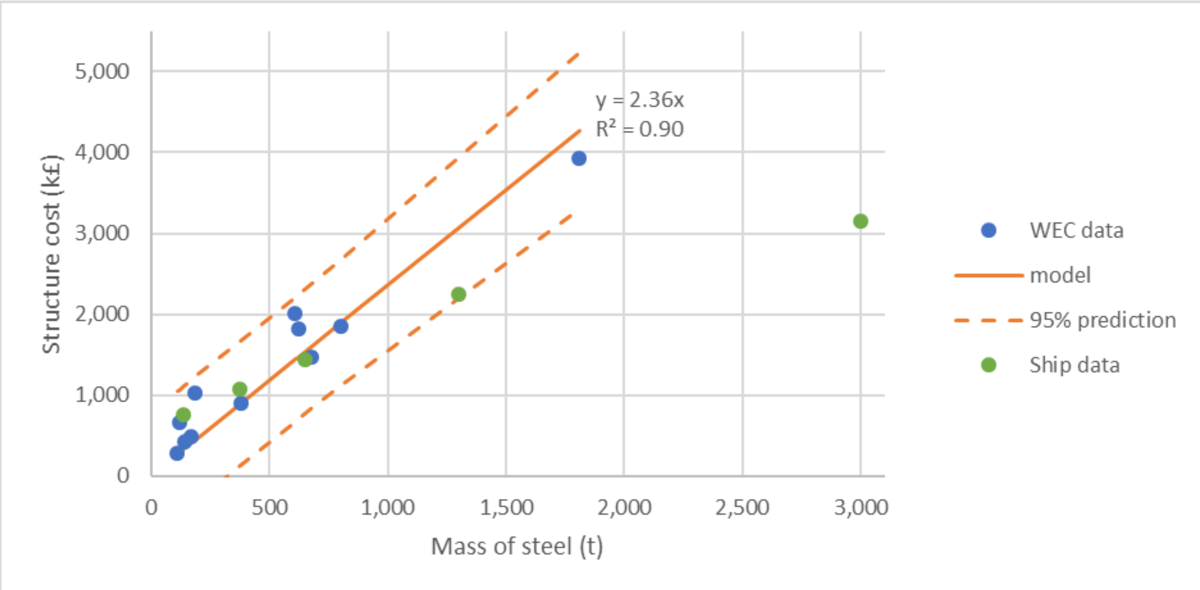


Figure 22: Cost of structure versus mass of steel.

The corresponding expression for steel WECs is then:

$$C_{\text{fab}} = c_{\text{fab}} \cdot M_{\text{steel}} \pm 776 \quad [€],$$

where c_{fab} is the fabricated cost in [€/kg] and the +/- value is an average for the 95% prediction interval. The values for c_{fab} for each type of structure is given in Table 15. Ideally more data is needed for larger structures to have more confidence in these values.

The data for ship hulls (some of which is outside the chart area) appears to show a shallower trend – possibly because it is a more mature sector but also because it easier to get a breakdown of costs that separates the cost of the hull only. The data for WTs (some of which is outside the chart area) appear to show a steeper trend – possibly because these costs are for the whole turbine, made up of several very different components to manufacture: nacelle, rotor, tower etc.

Table 15: Cost per mass for three types of structure. 95% prediction value is for the total cost and is an average across the range of mass that was evaluated.

Type of steel structure	c_{fab} (€/kg)	+/- 95% prediction interval (€)
WEC	2.36	776
Ship	1.22	/
WT	8.19	/

Relationships for Other Materials

The relationships for structure mass versus total volume and material cost versus structure mass, given in appendix D and E, respectively, are for steel only. For the other materials for which it is currently possible to compare in the tool, other sources of data were used to adjust these (assumed to be) linear relationships appropriately.

Unfortunately, there are far fewer examples of offshore structures that are made of these materials or data that is readily available. The characteristic values for each material contained within the Material lookup table in the tool (Table 12) can be updated or changed as required and it is also possible to add more material options.

F. Improvement Potential of Different Technologies

Analysis of cost reduction in electricity generating technologies suggests the level of cost reduction that can be expected over a given timeframe or rate of deployment depends partly on the maturity of the technology in question [22] [23]. Typically, this is characterised by an experience curve describing the rate of cost reduction – or learning rate. In [22], technologies are described as having low, medium or high learning rates. Learning rates can be used to predict future cost of energy based on the expected cost reduction of subsystems [24]. Similarly, in [25], maturity is used as a factor in determining the potential for reduction in cost and increase in efficiency in alternative WEC technologies over a time span of 25 years.

This is the basis of the TA score employed in the Scenario Creation Tool. A previous method re-arranged the experience curve formula and used low, medium and high learning rates to describe technologies [8]. However, it was decided to use a simpler formula here for calculating the score (see section 6.3.2), that multiplies the ratio of scenario cost (or power) to the SOA cost (or power) by an improvement potential factor β. β can take one of three values for low, medium and high and a description of each level is given in Table 16.

Table 16: Descriptions of the Improvement Potential Levels, taken from [8].

Improvement Potential	β	Description
Low	1	Mature technologies that have featured in previous wave energy development or in similar applications but are the subject of little active R&D. Technology that would likely require a high investment to achieve unit improvement.
Medium	2	Emerging technologies that are mostly new to wave energy development and similar applications or reviving technologies that are the subject of active R&D. Technology that would likely require a medium investment to achieve unit improvement.
High	3	Evolving technologies that may have featured in previous wave energy development or in similar applications but are the subject of extensive active R&D. Technology that would likely require a low investment to achieve unit improvement.

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