Open Sea Operating Experience to Reduce Wave Energy Costs

Deliverable D7.2

Operating data input for models of levelised and society cost and life cycle assessment for wave energy

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EXECUTIVE SUMMARY

This OPERA project deliverable D7.2 describes the global economic model developed and the methodologies employed for the economic analysis of an array of floating Oscillating Water Columns (OWCs). The global economic model calculates Levelised Cost of Energy (LCOE), Socio-economic Cost of Energy (SCOE) and performs a Life-Cycle Assessment (LCA).

The deliverable describes the components of the global economic model and how the methodology followed in its development and operation ensures that its calculations, inputs and structure lead to controllability and improved accuracy. It describes how an Operational Expenditure (OPEX) model, developed through activities undertaken within OPERA Work Package 6 (WP6), better reflects the influence of Operation and Maintenance (O&M) activities on project economics. The OPEX model estimates the financial and environmental costs of probable O&M activities and the impact that these activities will have on device availability over the operating lifetime. The OPEX model will be updated with data logged during the operational phases of the OPERA project. Inclusion of real in-sea operational data will improve the accuracy of the OPEX and global economic models' estimates and therefore reduce investment risk. The real sea data will be logged in an O&M framework that is also described in this deliverable. The inclusion of real sea data differentiates the global economic model from the previous state of the art in Wave Energy Converter (WEC) economic evaluation.

Within the OPERA project, the global economic model will be used to evaluate the economics of an array of "base case" floating OWCs. These base case devices comprise a spar buoy WEC, a Wells turbine, a conventional control methodology and mooring system. The economics of the base case array will then be compared to the economics of an array of devices comprising the base case WEC hull refitted with independently acting cost reducing innovations: advanced elastomeric moorings, a bi-radial air turbine, innovative control strategies and a shared WEC mooring arrangement. The results of the evaluation will be presented in a later OPERA deliverable (D7.3).

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ABBREVIATIONS AND ACRONYMS

AEP	Annual Energy Production
BiMEP	Biscay Marine Energy Platform
CAPEX	Capital Expenditure
EIA	Environmental Impact Assessment
COE	Cost of Energy
GVA	Gross Value Added
CW	Capture Width
CWR	Capture Width Ratio
EPBT	Energy Payback Time
ERA	Environmental Risk Assessment
EROI	Energy Return of Investment
GVA	Gross Value Added
GWP	Global Warming Potential
IxI	Industry by Industry
IO	Input-Output
LCA	Life-Cycle Analysis
LCOE	Levelised Cost of Energy
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operational Expenditure
OWC	Oscillating Water Column
PTO	Power Take-Off
RET	Renewable-energy and Energy-efficient Technologies
SCOE	Socio-economic Cost of Energy/Social Cost of Energy
SEA	Strategic Environmental Assessment
STD	Standard Deviation
WEC	Wave Energy Converter

1. INTRODUCTION

This document represents Deliverable 7.2 (D7.2) of OPERA's Work Package 7 (WP7).

OPERA is a European Commission funded project that ultimately aims to reduce the time to market of wave energy. Wave energy is an underutilised, clean and sustainable renewable energy source that has the potential to contribute to Europe's electricity demand and add significant job opportunities [1].

OPERA is tackling this challenge of uncertainty in Wave Energy Converter (WEC) projects and achieving its aims through the following objectives:

- Gather, analyse and share data obtained during the development, operation and decommissioning of a real world floating Oscillating Water Column (OWC) WEC deployed at the BiMEP test site in the north of Spain to better inform cost and energy yield estimates and,
- Undertake a technology de-risking case study; a floating OWC WEC on which four cost-reducing innovations will be tested, namely: advanced elastomeric moorings; a bi-radial air turbine; innovative control strategies; and a shared WEC mooring arrangement.

1.1 WP7 OBJECTIVES

OPERA's WP7, entitled, "Risk management, cost of energy and final assessment," gathers information from all other OPERA work packages to analyse the influence of their respective innovations on project economics and risk. At its completion, WP7 will have gained knowledge from technology developers and sea-trial data, resulting in guidance and recommendations for future WEC project economic analysis and risk assessments.

1.2 DELIVERABLE OBJECTIVES

An economic model has been assembled within WP7. Three economic calculations are executed within the model: Levelised Cost of Energy (LCOE), Life-Cycle Assessment (LCA) and Socio-economic Cost of Energy (SCOE) calculations. Since the model contains these three calculations, the deliverable refers to the model as the *Global Economic Model*. Each of the three calculations use common inputs and are interdependent. In addition to yield and Capital Expenditure (CAPEX) inputs, parametrically related to WEC rated power, the global economic model's calculations are informed by a new and sophisticated Operational Expenditure (OPEX) model.

The OPEX model was developed through work undertaken in the OPERA project's WP6 and is informed by data obtained during the operational phases of OPERA and logged in an

Operation and Maintenance (O&M) framework spreadsheet. The OPEX model, and inclusion of operating data, satisfies one of the key objectives of the OPERA project - to reduce the uncertainty associated with WEC OPEX estimation. In addition to estimating OPEX values, the OPEX model also has the flexibility to produce outputs indicating the environmental impact of probable O&M activities and their influence on WEC/array availability.

This deliverable has the following objectives:

- Indicate the state of the art of WEC techno-economic assessment,
- Describe how the inputs and structure of the global economic model facilitate control of the model's operation and customisation and,
- Explain how real sea operational data is incorporated into the global economic model through the project specific OPEX model and O&M logging framework spreadsheet.

1.3 DESCRIPTION OF WORK AND ROLE OF EACH PARTNER

The work on this deliverable was led by the University of Edinburgh, assistance was provided by Tecnalia. Both of these OPERA partners prepared technical notes reviewing available techno-economic models and a technical note describing of the global economic model. Additional OPERA partners (Kymaner, Oceantec and the University of Exeter) provided inputs for the latter technical note and the global economic model.

The University of Edinburgh combined the contributions of all the partners and drafted deliverable D7.2. The OPEX model development was undertaken by Tecnalia, while the integration of the OPEX model within the techno-economic model was led by the University of Edinburgh.

2. GLOBAL ECONOMIC MODEL CALCULATIONS

This section describes the different calculations contained within the OPERA global economic model. The three calculations contained within the global economic model are:

- Levelised Cost of Energy (LCOE),
- Life-Cycle Assessment (LCA) and,
- Socio-economic Cost of Energy (SCOE).

These calculations are described in sections 2.1, 2.2 and 2.3 respectively.

2.1 LEVELISED COST OF ENERGY

LCOE is the total CAPEX and OPEX costs associated with power generation, discounted to present day value, divided by the discounted energy produced throughout the technology's operational life; see equation (1),

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX}{(1+k)^t}}{\sum_{t=1}^{n} \frac{AEP}{(1+k)^t}}. \quad (1)$$

AEP in equation (1) is the Annual Energy Production, k is the discount rate and n is the number of years of the project. LCOE is a well-established metric for evaluating energy generation technologies. It is comparable to the market selling price/break-even price of electricity and requires fewer inputs than other purely financial indicators.

In addition to providing an ultimate indicator of the feasibility of a technology, the separate components of the LCOE calculation enable an evaluation of the main drivers of cost. For example, CAPEX can be subdivided into: structure, Power Take-Off (PTO), mooring system, electrical infrastructure and installation etc. OPEX can be subdivided into preventive and corrective O&M costs, lease rent, insurance, as well as decommissioning costs etc.

LCOE can be rearranged to calculate the NPV (Net Present Value) – which is the capital value, in nominal terms of a project today following summation of the depreciated annual cost and energy production terms, as indicated in equation (2),

$$NPV = \sum_{t=1}^{n} \frac{\mathrm{LCOE} \times \mathrm{AEP}}{(1+k)^t} - \mathrm{CAPEX} - \sum_{t=1}^{n} \frac{\mathrm{OPEX}}{(1+k)^t}. \quad (2)$$

NPV can be described as the "difference amount" between the sums of discounted cash inflows and cash outflows, and importantly, allows a cross project comparison of value for investment decisions.

Depending on the NPV, investment decisions change:

- If NPV < 0: Value would decrease despite the investment. This project should be rejected if the decision on whether to invest or not is to be made purely on monetary criteria. If other reasons for investing were to exist, such as for the public good, then the investor should consider these other benefits.
- If NPV = 0: The investment would neither result in value being added or taken away, i.e. cash neutral. Since the investment adds no monetary value in nominal terms, the decision on whether to invest or not should be based on other criteria.
- If NPV > 0: Value would be increased as a result of the investment. This indicates that the project is profitable and could potentially be invested in, unless the project results in other undesirable externalities such as pollution or wildlife habitat destruction.

The LCOE section of the model also yields the Internal Rate of Return (IRR) for a given project scenario. The IRR percentage represents the discount rate at which the project yields a neutral NPV value and is used to assess an investment's profitability. It can be considered as the rate of growth for a project investment and compared to the market rate;

$$0 = P0 + \frac{P1}{(1+IRR)} + \frac{P2}{(1+IRR)^2} + \cdots + \frac{Pn}{(1+IRR)^n} \quad (3)$$

Where P0, P1, P2, … Pn equal the cash flow periods respectively. The LCOE, NPV, IRR, and CAPEX per MW comparative economic measures are widely used throughout the energy sector to compare different technology generation costs.

2.1.1 LCOE TOOLS

The LCOE calculation contained within the OPERA global economic model is project specific. This allows full control of the model and ensures that it is fully compatible with OPERA project objectives, developments and innovation owner requirements. A number of pre-existing LCOE tools were evaluated and acted as comparative models prior to the development of the OPERA model. The following sub sections briefly describe a number of the LCOE models reviewed.

2.1.1.1 RETSCREEN

Clean Energy Management Software (usually referred to as RETScreen) is a free clean energy software package developed by the Canadian Government [3].

The software can be used to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs). The software also includes product, project, hydrology and climate databases (databases of wind, wave and current), a detailed user manual, and a case study based training course.

RETScreen uses *Microsoft Excel* macros and is developed and maintained by Natural Resources Canada's Canmet ENERGY research centre in Varennes, Quebec.

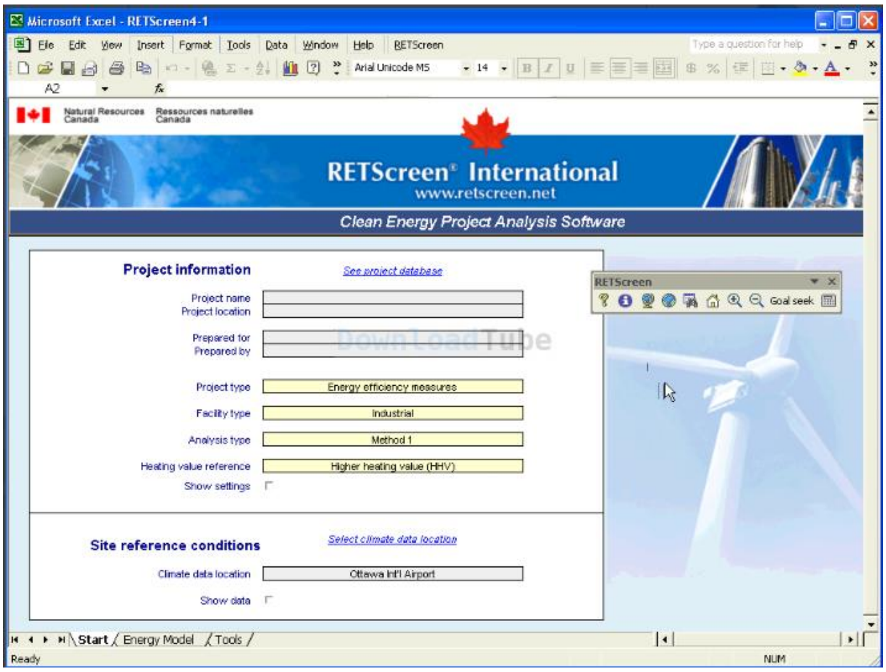


FIGURE 1: SCREEN SHOT OF RETSCREEN

2.1.1.2 NAVITAS-EXCEEDENCE

Navitas [4] is a financial software tool for ocean renewable energy developed by the Centre for Marine and Renewable Energy (MaREI) [5] and Exceedence [6]. A demonstration of Navitas is presented in [7].

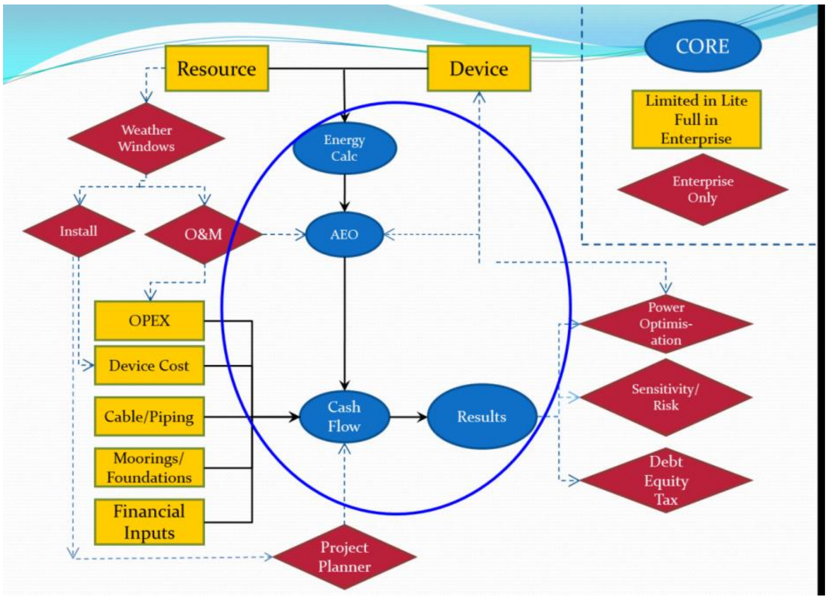


FIGURE 2: FLOWCHART OF NAVITAS ECONOMIC MODEL [4]

Key features of the Navitas software are:

- Full real-time integration of technical and financial inputs/outputs,
- The tool yields LCOE, IRR and NPV,
- Can be operated with varying levels of detail, with estimates or more detailed inputs,
- Extensive database of wind, wave and tidal resource for 24 locations and different device type characteristics,
- Allows for integration of user specified resource and device information,
- Allows for rapid testing and sensitivity analysis and,
- Enables optimisation.

2.1.1.3 WAVE VENTURE TE

Wave Venture TE [8] is a techno-economic assessment tool specifically designed for optimising the commercial performance of WEC systems. The tool was initially developed and verified through work undertaken for the TEO-WEC project by the Centre for Ocean Energy Research (COER) at Maynooth University [9] [10]. The tool has since been developed by Wave Venture [11] and now performs engineering analysis, operational simulation, financial analysis and numerical optimisation.

Key features of the Wave Venture TE software are:

- It provides an independent assessment of a technology as no third party performance data is required,
- Its simulations have been verified and validated,
- It models O&M activities from first principles to avoid arbitrary estimations,
- It allows rapid testing of parameter adjustment,
- It enables an evaluation of a concept (instead of just one deployment instance) and,
- It is designed for execution on High Performance Clusters (HPCs).

2.1.1.4 WAVEFARMER

WaveFarmer is a WEC array planning tool developed by Garrad Hassan (now DNV GL) [12]. WaveFarmer is the first commercial WEC array design tool. It optimises WEC array designs to maximize energy yield and return on investment, whilst minimizing risk. The software assesses a project's economic feasibility, optimising yield whilst ensuring that the design meets all pre-defined constraints. The tool has been released in four versions: commercial, educational, evaluation and research.

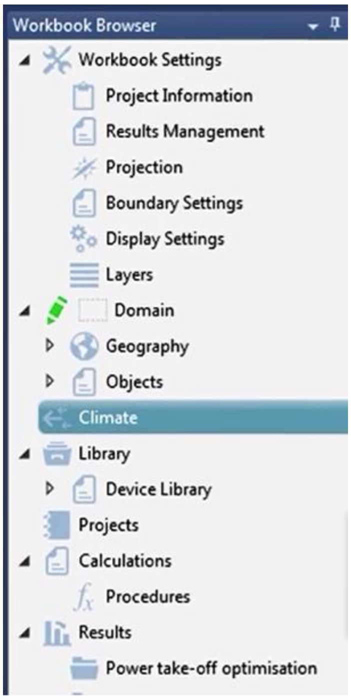


FIGURE 3: WAVEFARMER MENU

2.1.1.5 COE CALCULATION TOOL

The COE (Cost of Energy) Calculation Tool, developed by Julia Fernandez Chozas [13], is an open source tool which enables developers to undertake COE and scaling studies of their WECs. This open-access tool calculates LCOE for several locations; occurrence matrices for several deployment sites are already included in the model. Further to this, modellers can introduce additional occurrence matrices for testing. The model uses interpolation methods to assess the AEP of devices with power matrices of different resolutions to the occurrence matrices. The model also enables a sensitivity analysis of results.

The model also contains default values for equipment and component characteristics and costs. This guides early stage modellers through factors to be considered when evaluating the economics of their devices.

OPEX in the model is estimated as being a percentage of CAPEX.

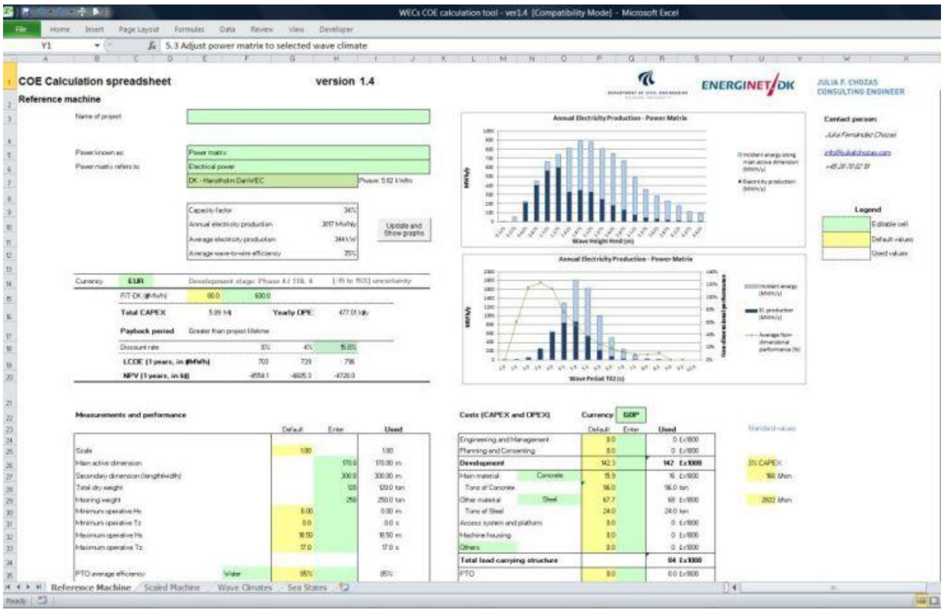


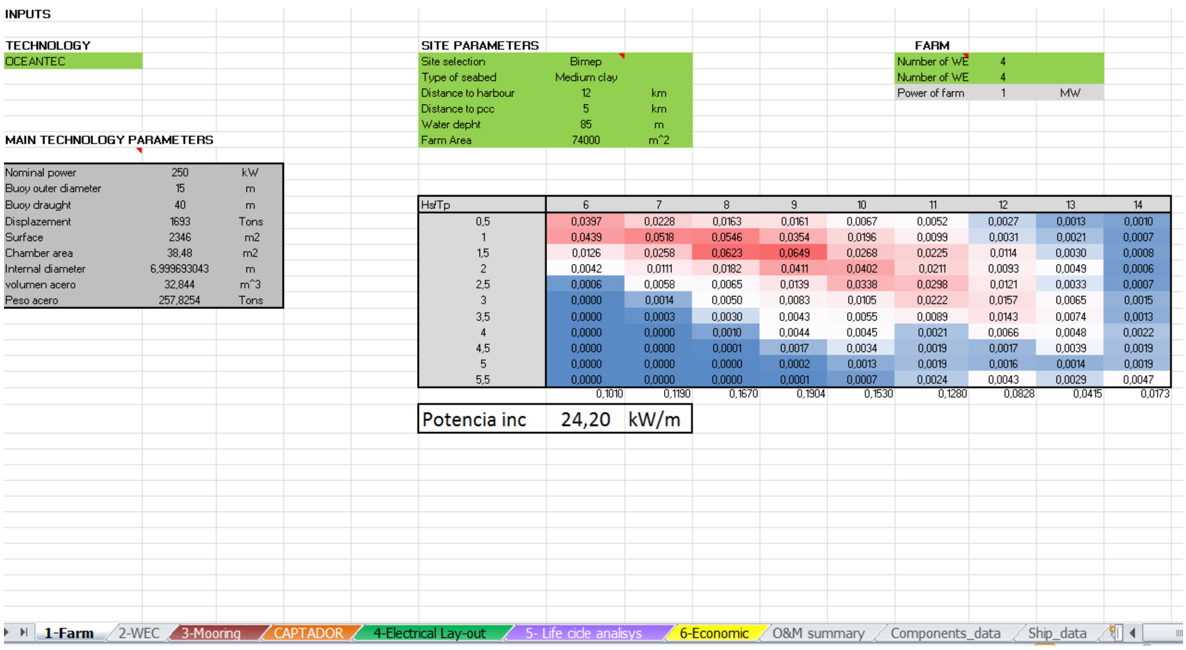
FIGURE 4: COE CALCULATION TOOL

2.1.1.6 UHINDAR

The UHINDAR project produced a techno-economic tool to evaluate the economics of an array of OCEANTEC devices. The project, led by Iberdrola Engineering and Construction, was partially funded by the ETORGAI Grant Scheme launched by the Basque Country Government, via the SPRI Group (a company seconded to the Basque Department of Industry, Innovation, Trade and Tourism) [14].

The tool developed through the UHINDAR project has several modules:

- Farm, where the general project inputs are defined,
- WEC, where the PTO efficiency and costs are calculated,
- Electrical layout, where the electrical losses, power quality and costs are calculated,
- Life-cycle analysis,
- Economics which calculates LCOE and,
- Auxiliary tabs specifying component vessel costs, as well as the O&M strategy.



INPUTS

TECHNOLOGY
OCEANTEC

MAIN TECHNOLOGY PARAMETERS

Nominal power	250	kW
Buoy outer diameter	15	m
Buoy draught	40	m
Displazement	1693	Tons
Surface	2346	m2
Chamber area	38,48	m2
Internal diameter	6,999693043	m
volumen acero	32,844	m^3
Peso acero	257,8254	Tons

SITE PARAMETERS

Site selection	Bimep	
Type of seabed	Medium clay	
Distance to harbour	12	km
Distance to pcc	5	km
Water depht	85	m
Farm Area	74000	m^2

FARM

Number of WE	4	
Number of WE	4	
Power of farm	1	MW

Hs/Tp	6	7	8	9	10	11	12	13	14
0,5	0,0397	0,0228	0,0163	0,0161	0,0067	0,0052	0,0027	0,0013	0,0010
1	0,0439	0,0518	0,0546	0,0354	0,0196	0,0099	0,0031	0,0021	0,0007
1,5	0,0126	0,0258	0,0623	0,0649	0,0268	0,0225	0,0114	0,0030	0,0008
2	0,0042	0,0111	0,0182	0,0411	0,0402	0,0211	0,0093	0,0049	0,0006
2,5	0,0006	0,0058	0,0065	0,0139	0,0338	0,0298	0,0121	0,0033	0,0007
3	0,0000	0,0014	0,0050	0,0083	0,0105	0,0222	0,0157	0,0065	0,0015
3,5	0,0000	0,0003	0,0030	0,0043	0,0055	0,0089	0,0143	0,0074	0,0013
4	0,0000	0,0000	0,0010	0,0044	0,0045	0,0021	0,0066	0,0048	0,0022
4,5	0,0000	0,0000	0,0001	0,0017	0,0034	0,0019	0,0017	0,0039	0,0019
5	0,0000	0,0000	0,0000	0,0002	0,0013	0,0019	0,0016	0,0014	0,0019
5,5	0,0000	0,0000	0,0000	0,0001	0,0007	0,0024	0,0043	0,0029	0,0047
	0,1010	0,1190	0,1670	0,1904	0,1530	0,1280	0,0828	0,0415	0,0173

Potencia inc	24,20	kW/m

1-Farm | 2-WEC | 3-Mooring | CAPTADOR | 4-Electrical Lay-out | 5- Life cicle analisys | 6-Economic | O&M summary | Components_data | Ship_data

FIGURE 5: UHINDAR MAIN PAGE

2.2 LIFE-CYCLE ASSESSMENT

Environmental Impact Assessments (EIAs) are used to evaluate, and build knowledge on the potential environmental impacts of project activities; in this case, the development and implementation of an ocean energy project [15]. Within the European Union, regulations on EIAs are established in the EIA Directive (85/337/EEC, amended by Directive 97/11/EC and Directive 2003/35/EC). EIAs can take a number of forms, including:

- Strategic environmental assessments (SEAs) [16].
- Environmental risk assessments (ERAs) [17].
- Life Cycle Assessments (LCA) [18].

In the case of OPERA, the EIA will quantify the environmental impact of a WEC array project and identify mitigations leading to less of an environmental impact. The LCA approach will be adopted for the OPERA project.

At the outset, boundary conditions for analysis must be specified. In the OPERA project, the LCA will focus on the environmental impact of the following project stages:

- Manufacturing,
- Installation,
- O&M over the lifetime of the facility.

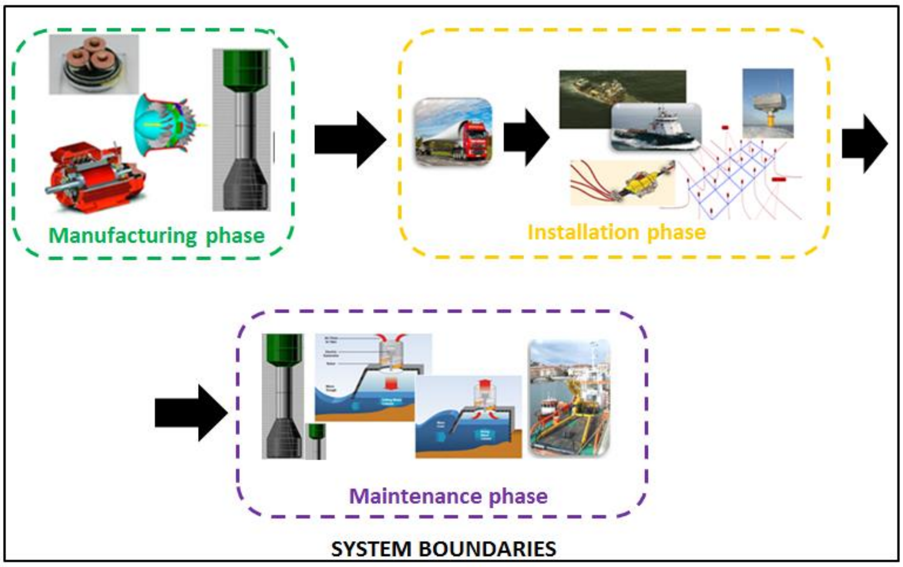


FIGURE 6: SYSTEM BOUNDARIES CONSIDERED IN THE LCA STUDY

Note, the manufacturing phase includes: the extraction and processing of raw materials, transport to the manufacturing site and construction of WEC components.

The potential environmental impact can be assessed according to the following impact categories:

- Energy Payback Time (EPBT),
- Energy Return of Investment (EROI),
- Global Warming Potential (GWP), expressed in terms of equivalent carbon dioxide.

The EPBT of a WEC array can be calculated as the number of years needed for the array to generate as much energy as the sum of the embodied energy of its whole life cycle, i.e. the primary energy from non-renewable sources spent during manufacturing, installation and maintenance stages.

The energy payback in years EPBT can be expressed using the following equation,

$$\mathrm{EPBT} = \frac{\mathrm{E}_p}{\mathrm{AEP}} \tag{4}$$

in which E_p is embodied primary energy.

EROI is an estimate of the life cycle energy performance of an energy generation system and can therefore be directly compared with EROI values for other renewable technologies [19]. The EROI of the WEC array can be defined as the electrical energy produced by WEC array over its service life, divided by the embodied energy of the WEC farm over its life cycle. See equation (5).

$$\mathrm{EROI} = \frac{\sum_{t=1}^{n} \mathrm{AEP}}{E_p} \tag{5}$$

The EROI has no units, and in plain terms as it represents 'how many times' the embodied primary energy of the WEC array has been saved during its service life.

GWP is estimated in terms of $kgCO_2/kWh$. This metric indicates the greenhouse gasses emitted throughout the life of the WEC array project. The metric accounts for the different emissions that are exhausted to the atmosphere by converting their impacts to the equivalent amount of CO_2 required to result in the same impact (over a time horizon of 100 years). The GWP figure can then be compared against estimates for other technologies. Note, here the functional unit that has been chosen to ensure comparability with other LCA results is "*1 kWh net of electricity from Wave Energy Converter produced and delivered to the grid*."

2.2.1 LCA TOOLS - OPENLCA

Similar to the global economic model's LCOE calculation, the LCA calculation within the model is project specific. As before, this enables full control of the calculation, ensuring that it is compatible with the other components of the global economic model and the OPERA project objectives, developments and innovation owner requirements. This is to ensure the aforementioned control reason. One LCA tool that was evaluated prior to the development of the global economic model's calculation was OpenLCA.

OpenLCA is an open source tool for performing LCA analysis [20]. It is structured so that in addition to the LCA results, it is possible to identify the main factors in a project that are causing the greatest environmental impact. The tool has a modular design and due to its open source nature is built to be developed by the programming community. The tool can operate using a range of free or licensed databases which are available to download [21].

2.3 SOCIO-ECONOMIC COST OF ENERGY

SCOE studies analyse a number of externalities to determine the social versus cost benefits of undertaking a particular project, see Figure 7. In OPERA, the SCOE study focuses on the impact of a WEC array project on job creation and the increase in both national and regional economic activity.

The SCOE procedure adopted in OPERA considers the spend due to the project in the areas of interest, i.e. the deployment region and country, accounted to the following cost centres:

- Manufacturing:
  - Hull
  - PTO
  - Mooring system,
- Installation,
- O&M,
- Decommissioning.

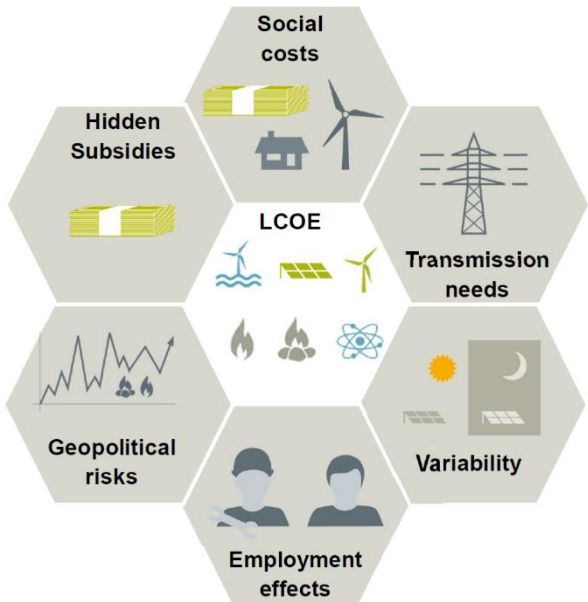


FIGURE 7: EXTERNALITIES CONSIDERED BY [22] AND [23].

Using Industry by Industry (IxI) Input-Output (IO) tables, the approach identifies which industries are engaged in each of the aforementioned cost centres. Coefficients (effects or multipliers) are then calculated through manipulation of the IxI IO tables to calculate how the spend in a region on each cost centre impacts economic activity and job creation.

The increase in economic activity is estimated as Gross Value Added (GVA) to the area of interest. For OPERA, GVA is defined as the net beneficial spend that is invested in the region due to a WEC array's deployment and operation.

Job creation is estimated in job years. This acknowledges that jobs created by the project will have a finite time. For example, jobs created by the manufacturing of the WECs are likely to only last as long as the manufacturing phase unless the same employees are engaged in an alternative activity at later stages.

2.3.1 SCOE TOOLS

Similar to the global economic model's LCOE and LCA calculations, the SCOE calculation within the model is project specific. Two pre-existing SCOE tools were evaluated prior to the development of the model. The following two sub sections briefly describe the SCOE models that were reviewed.

2.3.1.1 SIEMENS SCOE MODEL

The Siemens SCOE model was developed to present a, "true cost of energy" [22]. It accounts for the externalities shown in Figure 7. Figure 8 highlights how some externalities increase COE, thus making a technology less attractive (System costs + LCOE), whilst others reduce COE.

The Siemens SCOE model is a sophisticated model that accounts for a number of externalities in an effort to present the true economic cost of a new energy generation technology. The model has been used to compare nuclear, coal, gas, solar, onshore wind and offshore wind. It is expected that the model could also be applied to analyse a WEC array and that results could be similar to those of offshore wind.

However, a number of the externalities considered within the Siemens SCOE model require more thorough study and potentially public consultation e.g. social impact or geopolitical impact. This falls outside the scope of the OPERA project.

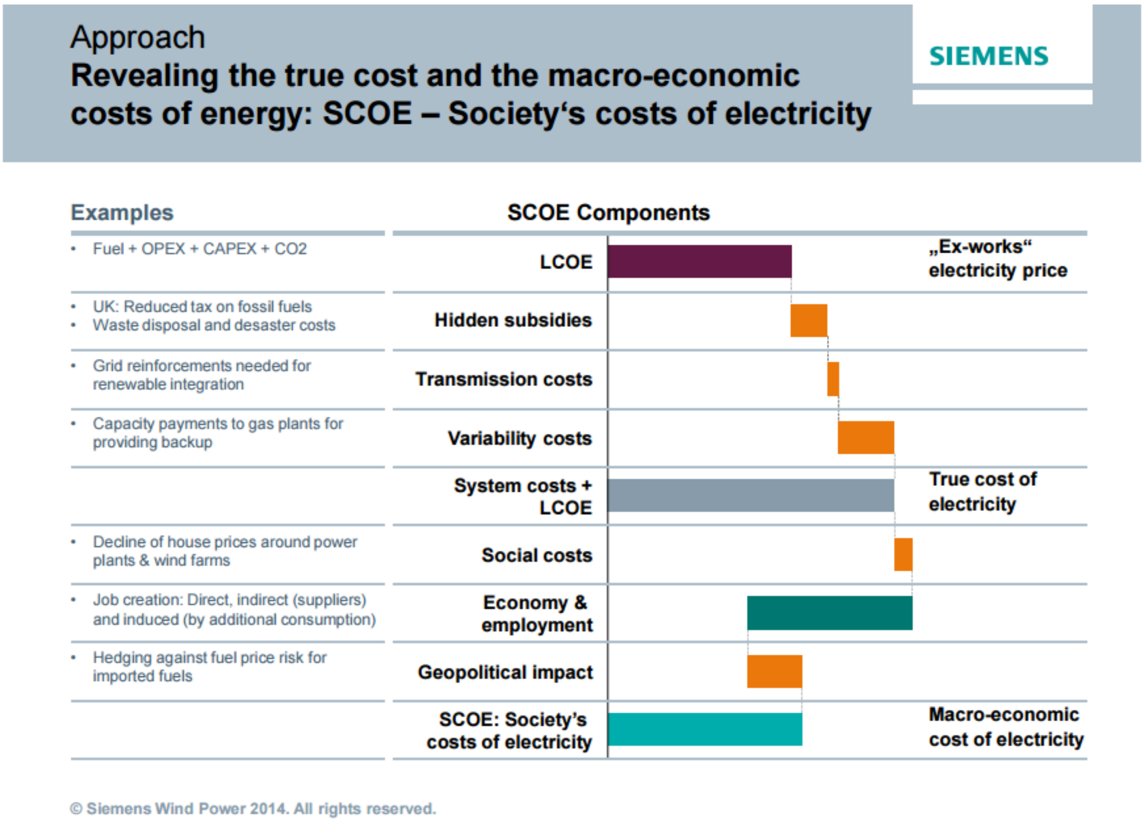


FIGURE 8: INDICATION OF THE DIFFERENT COST CENTRES AND EXTERNALITIES ACCOUNTED FOR WITHIN THE SIEMENS SCOE MODEL.

2.3.1.2 JOBS AND ECONOMIC DEVELOPMENT IMPACTS MARINE AND HYDROKINETIC MODEL

The JEDI (Jobs and Economic Development Impacts) tool has been developed by the National Renewable Energy Laboratory (NREL) [24]. The JEDI tool is a spreadsheet tool developed to demonstrate the economic benefits of investing in marine and hydrokinetic power systems in the USA. The tool is designed to be flexible and useful to modellers of various abilities.

It is set up to analyse wave, tidal, ocean current and river hydrokinetic technologies. It requires information on where the project is to be deployed, the year of construction and the size of the system. Using these inputs, it yields estimates of project cost, the number of jobs that will be created, the income of those working on the project and the economic activity that will be generated in the deployment region.

2.4 SUMMARY

This section has presented the LCOE, LCA and SCOE calculations that are executed within the OPERA global economic model. It has briefly described the calculations that are executed and presented a number of existing tools that were reviewed in advance of developing the global economic model.

The OPERA global economic model has been developed to build on the strengths of the reviewed models. The individual calculations within the model use similar inputs and are interconnected. Established analysis methods that have been widely used to evaluate power generation technologies are used, and the model is built in an *Excel* spreadsheet environment to allow for modeller customisation.

The following sections describe how the model is built to enable modeller customisation and how operational data, obtained during the operation phases of OPERA, is used to inform and improve the accuracy of the model's OPEX calculation, and thus the model's overall results.

3. METHODOLOGY FOR CUSTOMISING THE NUMERICAL MODEL

The OPERA global economic model developed in Work Package 7 (WP7) performs three calculations to allow an evaluation of a device or an array of floating OWCs. The model calculates: LCOE, LCA and SCOE.

Each of these calculations are described in sections 3.3, 3.4 and 3.5 respectively.

The global economic model is primarily adjusted by the selection of a WEC power rating. This input impacts on the number of devices in arrays and the size of devices and their subcomponents. This parameter therefore influences the amount of energy absorbed (influencing LCOE), environmental impact (influencing LCA) and cost of components and operations (influencing LCOE and SCOE). However, the structure and composition of the global economic model is such that its results can also be influenced through the modification of a number of other input parameters. This section describes the inputs and structure of the OPERA global economic model and how these facilitate customisation. Note the global economic model has been built in *Microsoft Excel*. Input data and calculations are separated and contained in different sheets of the *Excel* workbook. The sheets used for each of the calculations stated above are stated in section 3.3, 3.4 and 3.5.

Section 3.1 describes the model's inputs and section 3.2 describes the structure of the model and how data flows to and between the calculations.

3.1 GLOBAL ECONOMIC MODEL INPUTS

Three types of input are used in the OPERA global economic model: derived, internal and external. Derived inputs are those that have been obtained from OPERA project partners for the purpose of the OPERA project's economic models. Internal inputs are those that are generated by the activities that are undertaken in the OPERA project. They feed into the global economic model's calculations through the OPEX model which is discussed in chapter 4. External inputs are those used in the model obtained from external sources, such as learning rates, regional economic figures, vessel fuel consumption figures etc.

Sections 3.1.1 to 3.1.3 present a number of the derived, internal and external inputs.

3.1.1 DERIVED INPUTS

As stated, the OPERA global economic model is constructed to be primarily influenced by WEC power rating. This is a derived input. The WEC power rating influences the number of WECs required to achieve an array rating. WEC power rating also influences the physical size of the WECs, their PTOs and mooring system ratings. Changing these features impact both the cost of components and operations and also the environmental impacts of manufacturing and activity.

To accurately reflect the impact that changing WEC power rating has on cost and environmental impact, each of the OPERA project partners involved in the development of WEC components were consulted to obtain parametric corresponding coefficients. The coefficients provided by the OPERA partners (derived inputs) enable the calculation of financial costs and environmental impacts that are based on the WEC rated power specified by the modeller. The OPERA partners surveyed were:

- Kymaner - Biradial PTO developers. The biradial turbine is one of the cost reducing innovations to be tested during the OPERA project. After an initial test period at the Mutriku wave plant, the biradial turbine will replace the base case Wells turbine. Changing the WEC power rating changes the size of the biradial turbine.
- Oceantec - WEC developers and supplier of the base case components. In addition to providing information on the WEC dimensions, Oceantec also provided information describing how the Wells turbine (the base case PTO) and the original mooring system change with WEC rating.
- Tecnalia - OPERA project coordinators, operational logistics management and advanced control system design. Tecnalia have provided information about operational logistics, including information detailing equipment and vessel fuel consumption. The advanced control algorithm is another cost reducing innovation being trialled during the OPERA project. It will result in a minimal increase in Capital Expenditure (CAPEX) but has the potential to improve AEP and increase reliability and survivability, thus reducing OPEX costs.
- The University of Exeter - Elastomeric tether developers. The elastomeric tether is another cost reducing innovation being tested during the OPERA project. It will replace the conventional base case mooring system chain. Changing the WEC power rating will require a change in the properties of the tether since the mooring loads will change.

3.1.2 INTERNAL INPUTS

As previously indicated, the global economic model's internal inputs are the outputs of the OPEX model that is discussed in chapter 4 of this deliverable. For reference, WP6 focuses on improving the identification of the lifetime offshore logistics costs of floating OWCs by reducing uncertainty. It also intends to optimise offshore OPEX costs incurred through operations by using 'real sea' test data calibrated models and modified lessons learned operational guidelines. The outputs of the OPEX model that feed into the global economic model as internal inputs are:

- The cost of operations (in the form of annual costs)
- Availability,
- Litres of fuel consumed.

3.1.3 EXTERNAL INPUTS

The global economic model's data external inputs are obtained from a range of sources, including scientific literature, economic figures, LCA databases etc.

One key factor that determines the number of external inputs is the scenario chosen for analysis. In particular, the scenario specifies the geographical location of the project. The scenario therefore dictates:

- The resource at the deployment site and therefore the AEP of the WEC/array,
- The deployment site's characteristics and distance from port and therefore equipment specifications and logistics,
- The capacity of the region of deployment in terms of industries present and economics.

It should also be noted that the scenarios were, and should be, specified to be commercially viable. For example, it is not rational to evaluate the commercial viability of a project based on the characteristics of a single demonstration device. It is widely accepted that for WECs to be commercially viable they will have to be deployed in arrays. Deployment of devices in arrays will enable cost savings through economies of scale, learning and sharing of operations.

Two scenarios are evaluated in the OPERA project. One in which an array of devices is deployed off the coast of the Spanish Basque Country, and the other in which an array of devices is deployed offshore of the Scottish Orkney Islands. For both scenarios, two array sizes were specified; a 10 MW array and an 18 MW rated capacity array. These array sizes were considered realistic target scenarios.

Regarding global economic model customisation, as stated, the primary input that will be adjusted in the model is the WEC power rating. Further customisation could be achieved through modification of the derived inputs. This customisation would be required if different components were analysed. The internal inputs are the most restricted of the model. Recall, these inputs are the outputs of the OPERA OPEX model, see chapter 4. The external inputs can be adjusted to reflect different project properties and deployment region and site characteristics.

3.2 STRUCTURE OF OPERA'S GLOBAL ECONOMIC MODEL

This section describes the structure of the global economic model. Figure 9 depicts how data flows in the model. It shows how the different inputs described in sections 3.1.1 to 3.1.3 feed into the LCOE, LCA and SCOE calculations contained within the global economic model and how information flows between the calculations, culminating in the output streams.

The derived inputs that feed into the LCOE calculation influence the calculation of CAPEX and AEP. Recall, in addition to WEC rated power, the derived inputs are generally guided by OPERA project partners and are cost coefficients parametrically related to WEC rated device power. The derived inputs that feed into the LCA calculation are values that indicate the energy required to manufacture the technologies analysed in the OPERA project and environmental impact of the manufacturing processes. The derived inputs that feed into the SCOE model include information from the OPERA project partners relating to the source of components (from inside or outside the region of interest).

The internal inputs (outputs of the OPEX model, see chapter 4) that feed into the LCOE model are the annual OPEX costs and availability values that influence the AEP. The annual OPEX costs also feed into the SCOE calculation. The internal inputs that feed into the LCA model account for the environmental impact of the O&M activities that take place throughout the lifetime of the project.

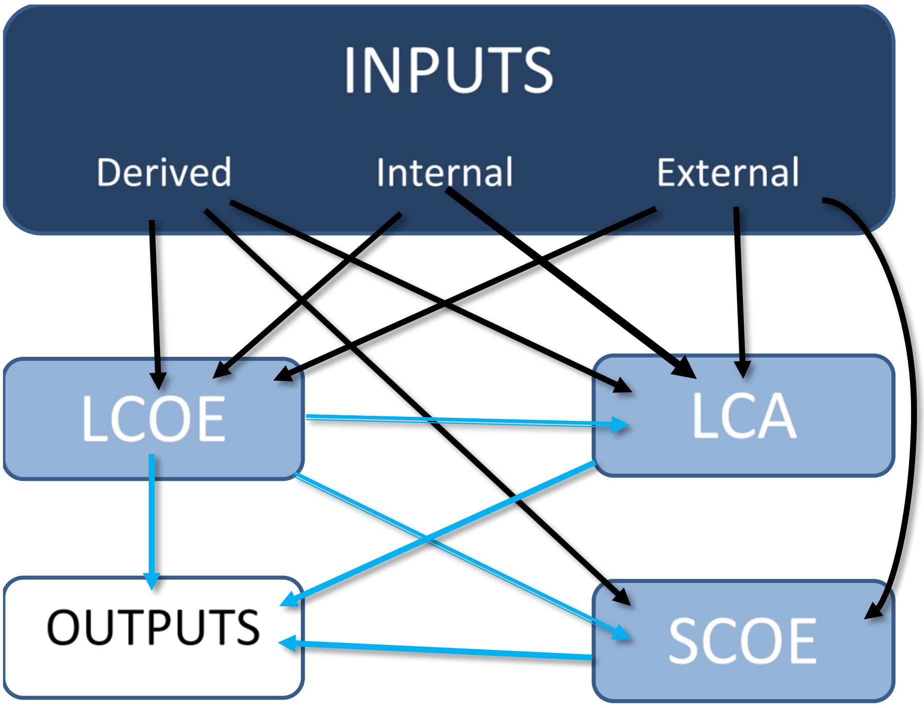


FIGURE 9: FLOW OF DATA WITHIN THE OPERA GLOBAL ECONOMIC MODEL.

The external inputs, based on the scenario chosen, feed into the LCOE calculation influencing final CAPEX, OPEX and AEP. An interest rate depreciates AEP and annual OPEX to present day values whilst site resource influences AEP and site characteristics (e.g. depth) influence WEC device properties and therefore the CAPEX of certain components (e.g. mooring system). The external inputs that feed into the LCA calculation include embodied energy and CO_2 related to materials, energy input and CO_2 emissions associated with manufacturing processes and fuel consumption and CO_2 emissions related to transport modes. The external inputs that feed into the SCOE calculation are those that are used to relate project spend to GVA and jobs created. These include economic IxI IO tables.

3.3 LEVELISED COST OF ENERGY

This section describes how the LCOE calculation is executed within the OPERA global economic model. The LCOE calculation can be written as,

$$LCOE = \frac{CAPEX+\sum_{t=1}^{n}\frac{OPEX}{(1+k)^n}}{\sum_{t=1}^{n}\frac{AEP}{(1+k)^n}}. \tag{6}$$

Equation (6) is a repeat of equation (1), but is repeated here for convenience.

The CAPEX term of equation (6) is the summation of all the Capital Expenditure costs. This information is primarily obtained through use of the values provided by the OPERA project partners. These coefficients are the derived inputs discussed in section 3.1.1 (Recall that these values are parametrically related to WEC power rating). However, since the global economic model is built in *Excel*, the flexibility exists to include alternative CAPEX figures alongside, or instead of the parametric values. WEC power rating is set by the modeller in the '*Inputs (Site&AEP)*' tab sheet of the OPERA global economic model. The parametric values provided by OPERA project partners are contained within the '*Lookuptables'* tab sheet and the CAPEX values are summed and presented in the '*CAPEX Calculation'* tab sheet.

The OPEX term of equation (6) is generated by the OPEX model described in chapter 4. The OPEX model yields estimates of annual OPEX costs. These are summed and converted to present day values using a discount rate, k, for the number of years in the project lifetime, n. The OPEX models results are contained within the '*OPEX model (Summary)'* tab sheet. The OPEX model's inputs, discount rate and number of years in the project's lifetime are set by the modeller in the '*Inputs (Site&AEP)'* tab sheet.

The CAPEX term is multiplied by a learning rate which is determined by the number of devices deployed, to account for the cost savings due to economies of scale, learning and sharing of operations etc. A learning rate of 14 % was used in the OPERA project; this corresponds to the middle scenario chosen by [25].

The AEP term of equation (6) is calculated in the '*Inputs (Site&AEP)'* tab sheet. In the OPERA project, the AEP value is calculated using equation (7).

$$AEP = P\eta YAi \tag{7}$$

P in equation (7) is the array power rating, which is set by the modeller in the '*Inputs (Site&AEP)'* tab sheet, η is the Capture Width Ratio (CWR) - which is the ratio of Capture Width (CW) over device width. CW is the ratio of power captured to wave power per meter crest. The CWR value used in equation (7) was taken from a database of CWRs [26]. The value chosen was the average CWR calculated for heaving point absorbers, 16 %. Of the heaving point absorbers surveyed for the database, there was a Standard Deviation (STD) of 10 % on the CWR value. Y in equation (7) is the number of hours in a year and A_i is availability. A_i is an output of the OPEX model.

3.4 LIFE-CYCLE ASSESSMENT

This section describes how the LCA calculation is executed in the OPERA global economic model.

Two LCA approaches are taken within the global economic model to estimate the environmental impact of the WEC projects. In the first approach, equivalent embodied CO_2 (over a time horizon of 100 years) is calculated. The resulting carbon dioxide equivalent calculated is used to calculate the total GWP of the WEC projects. In the second approach, project embodied energy is calculated. The resulting overall embodied energy is used to calculate the EPBT and EROI of the projects.

In both approaches, coefficients have been obtained that relate the technologies manufactured and processes/activities undertaken to equivalent embodied carbon and embodied energy. These coefficients are multiplied by volumes, masses and lengths, depending on the component parts or processes/activities, to yield embodied carbon and primary energy. The coefficients were primarily obtained from the *Ecoinvent* database [27]. In addition to this, OPERA project partners also provided details on the embodied carbon and energy of particular components and activities. For example, Tecnalia provided information on the fuel consumption of the vessels that will be operated during offshore activities.

The LCA coefficients related to the manufacture and installation of the WECs are contained in the '*Lookuptables'* tab sheet in the global economic model. These coefficients are parametrically related to WEC power rating. The OPEX model yields estimates of litres of fuel consumed during the O&M; this data is presented in the '*OPEX model (Summary)'* tab sheet. The LCA calculations are performed in the '*LCA'* tab sheet of the global economic model.

3.5 SOCIO-ECONOMIC COST OF ENERGY

This section describes how the SCOE calculation is executed in the OPERA global economic model.

As with the LCA, two approaches are taken within the global economic model to estimate the social impact of the WEC projects. The first approach estimates the net economic impact in regions of interest due to the WEC arrays. This is estimated using the GVA metric. The second approach estimates the job creation due to the spend in the regions of interest. This is estimated in job years. The primary regions of interest in OPERA are those in which the WEC deployments are proposed: as previously stated these are the Basque Country for the Spanish scenario and Orkney for the Scottish scenario.

Both approaches require the calculation of the gross spend on the project. In the global economic model, the gross spend of the project is divided into the following cost centres:

- Manufacturing:
    - Hull,
    - PTO,
    - Mooring system,
- Installation,
- O&M and,
- Decommissioning.

The gross spend on manufacturing and installation is the same as the CAPEX costs used in the LCOE calculation; the gross spend on manufacturing and installation is parametrically related to the WEC power rating and obtained from the '*Lookuptables'* tab sheet. The gross spend on O&M is the same output of the OPEX model that is used in the LCOE calculation. It is obtained from the '*OPEX model (Summary)'* tab sheet. The decommissioning cost is also estimated using the OPEX model.

The activities covered by these four cost centre blocks can be undertaken simultaneously. For example, manufacturing will occur at the start of the project, but it is likely that for large arrays that manufacturing will be ongoing as installation commences. Further to this, in the final years of manufacturing, devices in the array may be operational (O&M), whilst others are being installed. At the end of the project, it is likely that the first devices to be decommissioned will be those that were installed first. It is equally likely that devices installed later will still be operational as the first devices are being decommissioned. This is accounted for in the '*SCOE'* tab sheet of the global economic model. Importantly, although activities can be concurrent, they are not assumed to be inter-dependent.

3.5.1 GROSS SPEND TO GVA AND JOB CREATION ESTIMATES

This section describes the steps taken to convert the gross spend on each cost centre into economic impact and job creation.

The gross spend is converted to net spend through a series of ready reckoners. The ready reckoners account for how the project's gross spend will not be purely additional investment in the area under consideration, for example, components and services will be bought in from elsewhere or the project may reduce the activities of industries in other areas in the region etc. The ready reckoners considered are:

- Deadweight,
- Leakage,
- Displacement,
- Substitution.

These ready reckoners are discussed in ANNEX I. The ready reckoner information is taken from the '*Lookuptables'* tab sheet of the global economic model. Equation (8) shows how the ready reckoners are used to calculate the Net Spend (NS) on a particular cost centre.

$$NS = [GS \times (1 - DW) \times (1 - L) \times (1 - DP) \times (1 - S)]. \quad (8)$$

Where GS in equation (8) is the gross spend on a particular cost centre and DW, L, DP and S are the Deadweight, Leakage, Displacement and Substitution ready reckoners respectively.

GVA and job creation, due to the net spend on a particular cost centre in a region of interest, is then calculated by multiplying the net spend by effects. Effects are calculated through manipulation of Leontif matrices, see ANNEX II. In the OPERA global economic model, type II effects are calculated to estimate the economic impact of, and job creation due to net spend.

GVA and job creation effects are calculated through equations (9) and (10) respectively.

$$G_{eff,j} = \sum_i w_i L_{i,j} \quad (9)$$

$$E_{eff,j} = \sum_i g_i L_{i,j} \quad (10)$$

$G_{eff,j}$ in equation (9) is the GVA effect for industry - j (industry associated with column j of the IxI IO matrix) that is used to estimate GVA. g_i is the GVA of industry i (industry associated with row i of the IxI IO matrix), in the region of interest, divided by the column total of the same industry. $L_{i,j}$ is the cell of the type II inverse Leontif matrix (see ANNEX II) that corresponds with industries i and j.

$E_{eff,j}$ in equation (9) is the employment effect for industry j that is used to estimate job creation. w_i is the Full-Time Equivalent (FTE) employment for industry i divided by the column total of the same industry.

The GVA and employment effects (calculated using equations (9) and (10)) for particular industries are multiplied by the net spend on the cost centres that engage those industries. These sums yield GVA and job creation figures. GVA can be summed over the lifetime of the project. Recall, job years should be calculated since some jobs (i.e. in manufacturing) may not last the duration of the project. The GVA and employment effects are contained in the '*Leontif II'* sheet of the global economic model.

3.6 MODEL UNCERTAINTY

Incorporation of data obtained during the real sea operation of the floating OWC improves the accuracy of the global economic numerical model's results. Chapter 4 discusses both the OPEX model that estimates OPEX costs and availability and the O&M logging framework used to ensure suitable information is gathered for input into the global economic model's OPEX model.

However, despite improvements in OPEX estimation, uncertainty still exists in CAPEX and AEP estimates. To account for this, different conditions are run within the model: optimistic, middle and pessimistic. These conditions are based on OPERA project partner estimates. The conditions comprise of the following states:

- Optimistic – Greatest potential AEP, Lowest potential CAPEX,
- Middle – Average AEP, Average CAPEX,
- Pessimistic – Lowest potential AEP, Greatest potential CAPEX.

These conditions enable a sensitivity study to determine the range of potential model outputs.

Note, the conditions influence the LCOE and LCA calculations as expected, i.e. an optimistic condition yields the best (lowest) LCOE and results in the lowest environmental impact whilst a pessimistic condition yields the worst LCOE and the greatest environmental impact etc. Notably however, the SCOE calculation is not directly influenced by AEP, and the greater the CAPEX, the greater the project investment and therefore benefit to the economy; unless the large CAPEX were to cause the project to fail.

4. OPERATING DATA INPUTS

In line with the aims of the OPERA project, the global economic model is updated with real sea operating data. The inclusion of operational data through a project specific OPEX model improves the accuracy of the estimates made by the global model [28]. The OPEX model estimates the lifetime financial and environmental costs of preventive and corrective operations and their impact on availability.

The OPEX model was developed through work undertaken in OPERA's Work Package 6 (WP6). The specific objectives set when developing the model were as follows:

- Develop a tool that will more accurately represent the logistical requirements associated with a floating OWC,
- Enable the identification of approaches for optimizing O&M activities with a view to reducing lifetime costs,
- Enable the improvement of the current approaches to undertaking offshore operations,
- Develop a tool that will yield outputs for incorporation into a global economic model that evaluates the economics of a floating OWC,
- Develop a tool that will present guidelines that minimise the risk and costs associated with offshore operations on WECs.

Integration of the OPERA OPEX model within the global economic model improves the accuracy of the global economic model over the state of the art. Due to the nascent nature of the wave energy industry, OPEX is often simply included in economic models as a percentage of lifetime costs or CAPEX. This is due to, and can result in, large levels of uncertainty and investment risking. Despite operational data being recorded for a relatively short period of time (roughly 2 years of operational data will be recorded during the OPERA project), the sophistication of the OPEX model is such that it is able to estimate lifetime costs through the extrapolation of the measured data.

The input factors considered in the OPEX model and outputs are described in section 4.2. For a complete description of the OPEX model, see OPERA deliverable D6.2 [28]. Before discussing the OPEX model, section 4.1 describes the data logging framework spreadsheet that has been developed to ensure that the data required as input to the OPEX model is recorded for each offshore operation undertaken.

4.1 DATA RECORDING - O&M LOGGING FRAMEWORK

An O&M logging framework spreadsheet has been produced to streamline the input of operational data into the OPEX mode. The framework ensures that the correct information is obtained by the OPERA project partners involved in the operational logistics of the project. Figure 10 shows how operation information recorded is transferred into the OPEX model.

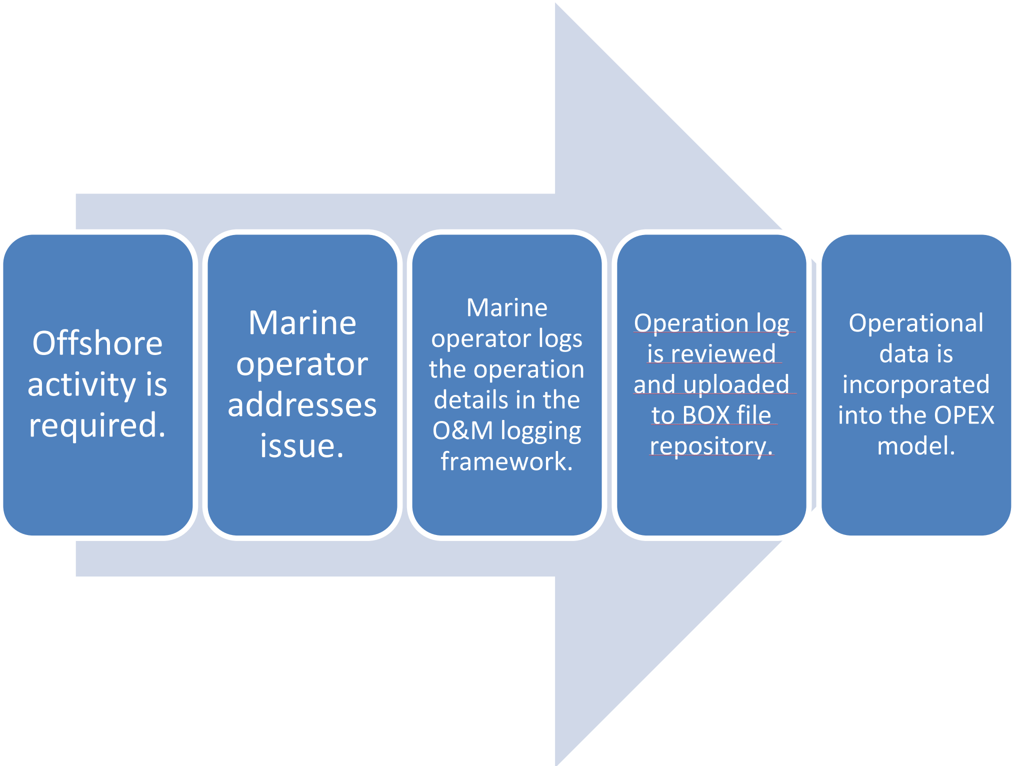


FIGURE 10: DEMONSTRATION OF OPERATIONAL DATA FLOW (OPERATION TO OPEX MODEL)

The O&M logging framework spreadsheet was drafted through a collaboration between OPERA WP6 and WP7 partners. Partners from both WPs were involved to a) ensure that appropriate data, and an amount of data is recorded, and b) to ensure that the expectations are realistic for those undertaking the operational and logging the activities.

The O&M framework spreadsheet records all the offshore operation activities, planned and unplanned. Figure 11 lists the items that are recorded in the planned and unplanned checklist sheets of the O&M logging framework. In addition to the items listed in Figure 11, the checklist sheets of the O&M logging framework also require the inclusion of a time stamp.

Schedule (Frequency)	Action needed	H_s max (m)	Failure effect	Impact on plant operations
Impact on operation	Est. duration (hrs)	Equipment	Failure cause	Action taken
Item ref. no	Actual duration (hrs)	Personnel	Item operation mode during failure	
Item details	Location (Onsite or port)	Parts/consumables	Detection method	
Priority	Vessels	Failure mode/ Mechanism	Impact on plant safety	

Planned O&M	Planned and Unplanned O&M	Unplanned O&M

FIGURE 11: LIST OF ITEMS RECORDED IN THE O&M LOGGING FRAMEWORK'S PLANNED AND UNPLANED CHECKLISTS

Further to the checklist, the O&M logging framework requires that operators fill out a more detailed log sheet for each activity undertaken; planned and unplanned. The items detailed in the log sheets are divided into several categories: onshore resources, offshore resources, Health and Safety (H&S), weather forecast and an activity log. The details of the items recorded for each of these categories are presented in Table 1 to

Table 3.

Figure 10 shows how the data recorded in the O&M logging framework spreadsheet checklists and logging sheets flows through to the OPEX model. The inputs will ultimately influence each of the global economic model’s component calculations: LCOE, LCA and SCOE.

TABLE 1: ONSHORE AND OFFSHORE RESOURCES LOGGED IN THE O&M LOGGING FRAMEWORK. *‘NUMBER’ IS ONLY LOGGED FOR ONSHORE RESOURCES.

Onshore & Offshore Resources	
Equipment	Type
	Name
Personnel	Type
	Number
	Hours
Parts/ consumables	Item
	Number/weight
	Used
On-land transport	Type
	Name
	Number*
	Location

	Location Fuel consumed (m^3)

TABLE 2: H&S LOGGED IN THE O&M LOGGING FRAMEWORK.

H&S	
Safety induction, talks, drills etc.	Number
	Comments
Recording of accidents	Number
	Comments
Recording of injuries	Number
	Comments

TABLE 3: WEATHER FORECAST AND ACTIVITIES LOGGED IN O&M LOGGING FRAMEWORK.

Weather Forecast	Activity Log
Forecast number	Activity
Forecast duration	Resources
Date	Activity undertaken from
Min-Max wave height	Activity ended
Min-Max wave period	Max wave height
Min-Max wind speed	Max wave period
Min-Max tidal current velocity	Max wind speed
	Max tidal current velocity
	Initials

4.2 OPEX MODEL

The OPERA OPEX model is the key component that differentiates the global economic model from other economic models. Operational data obtained from real sea operating experience, and logged though the O&M logging framework spreadsheet described in section 4.1, is used to update the OPEX model, which ultimately reduces uncertainty in the estimates of the global economic model. As previously discussed, the OPEX model reflects how both preventive and corrective operations influence project cost, environmental impact and device/array availability.

This section describes the inputs and outputs of the OPERA OPEX model and the factors considered by the model. As previously stated, the model is fully described in the OPERA project's deliverable D6.2 [28].

4.2.1 INPUTS - LOGGING OF OPERATIONAL DATA

The OPEX model requires certain inputs to enable the accurate execution of the model. The following points list and, where required, briefly describe the inputs to the OPEX model:

- Resource time series; This information is input into a Weather Window Waiting Time tool that estimates the impact of weather at site on operations. Specifically, it estimates average wait times and the standard deviation. The Weather Window Waiting Time tool was developed specifically for the OPERA project through WP6 activities. The tool is described in ANNEX II of OPERA deliverable D6.2 [28]. The inputs that the Weather Window Waiting Time tool requires (significant wave height; peak period; wind speed and direction; and wave direction) are input in terms of hourly records. The modeller must also indicate the condition thresholds that are required for activity to take place, e.g. maximum permissible wave height, etc.
- Project life (years).
- Distance to port (km); This is the distance from port to the site and therefore the distance travelled by vessels tending to the floating OWC.
- Working day period (hours).
- Initial year (year).
- Vessel data; Data on the vessel types available. Vessel data obtained is used a) to input into the financial and environmental cost and availability calculations and b) to decide on appropriate vessels for certain activities.
- Number of operations per farm.

4.2.2 MODELLING OF EXPECTED OPERATIONS

In order for the OPEX model to estimate the financial and environmental cost of operations and their impact on availability, it needs to know certain information about the operations that are likely to take place. This information is built up from the data gathered in the O&M logging framework spreadsheet described in section 4.1. The OPEX model's operations record will grow as the OPERA project progresses and as further data is captured from the real sea deployment of the technologies under investigation in the OPERA project. The data describing the expected operations define the technologies in operation and the particular maintenance plan inputs.

The following list indicates the data that is logged to describe each operation:

- Item ref. no,
- Item details; Details of the component that requires the operation,
- Planned operation; A value between 0 and 1. A value of 1 indicates that the planned operation is required on an annual basis,
- Uncertainty level; Deviation between failure rates. Uncertainty levels increase from 1 to 4. A value of 1 indicates 0.001 STD/Mean; 2 indicates 10 STD/Mean; 3 indicates 50 STD/Mean; and 4 indicates a Poisson - Exponential Distribution,
- Mean time between failures (1/year),
- Category; Failures are defined as incipient, Critical or Degradation,
- Failure mode; Type of failure,
- Failure effect on the power production (0 % - 100 %); How much does the failure impact production,
- Action needed; Description of the operation's activities,
- Est. duration (hours); Duration of operation, not including travel time,
- Location - Location of operation; onsite or at port,
- Vessels; Name of vessels required,
- Equipment; Equipment used and cost,
- Personnel; Personnel required and cost,
- Parts/consumables; Parts/consumables required and cost,
- Significant wave height (m); Max operational wave height,
- Tow required (Yes/No); Is a towing operation required,
- Mounting time (h); Time for mounting/unmounting the device,
- No. operations,
- Preparation time (h); Time required working at port prior to operation,

Further information about the operation descriptions is found in OPERA deliverable D6.2 [28].

4.2.3 OUTPUTS - INTEGRATION WITH GLOBAL MODEL

As discussed, the OPEX model considers each of the inputs and operation descriptions described in sections 0 and 4.2.2 to estimate the financial and environmental costs of the operations that are likely to occur over the lifetime of the project, and their impact on availability.

Specifically, the OPEX model outputs are:

- The cost of operations (in the form of annual costs),
- Availability,
- Litres of fuel consumed.

Owing to the OPEX model's integration with the global economic model, these calculated outputs act as internal inputs to the other streams of the OPERA global economic model. The cost of operations influences the expenditure on O&M activities. This cost impacts on both the LCOE and SCOE calculations. A greater spend on O&M activities increases the outgoings of the project and therefore increases the LCOE. A greater O&M spend also increases economic activity and engagement with the industries involved in the O&M activities improving the SCOE.

The availability value influences the revenue generated by the project since it determines the ocean energy resource converted by device/array. The revenue influences the global economic model's LCOE calculation through its calculation of AEP.

The litres of fuel consumed value influences the environmental impact of the project and therefore the LCA calculation.

In summary, the OPEX model is updated with data recorded on the operations that take place during the real sea testing phases of OPERA. The data, recorded in the O&M logging framework spreadsheet described in section 0, is input into the OPEX model. This data and the factors accounted for by the OPEX model, described in section 4.2.2, ultimately yield estimates of the financial and environmental costs of the operations that are likely to occur during the operation of a floating OWC and their impact of the availability of the device. The outputs of the model are therefore more representative of what could be expected during the operation of a wave energy project. The accuracy of the model's outputs is improved over the conventional approach taken for the calculation of OPEX costs in which they are estimated as either a percentage of CAPEX or lifetime costs. As discussed, this feature differentiates the OPERA global economic model from the previous state of the art in the techno-economic analysis of WEC projects.

5. CONCLUSIONS AND FURTHER WORK

A global economic model has been developed within OPERA's WP7 to analyse an array of floating Oscillating Water Columns (OWCs). The global economic model calculates Levelised Cost of Energy (LCOE), Socio-economic Cost of Energy (SCOE) and performs a Life-Cycle Assessment (LCA). This deliverable has described how the architecture of the global economic model and methodology adopted, both in the development the model and the recording of real sea operational data, ensures that the model is well controlled and has an improved accuracy over the previous state of the art.

This deliverable presented the calculations that are executed within the global economic model and a brief review of a number of other tools that have been developed to undertake techno-economic analysis of power generation technologies. The deliverable then provided a brief description of the calculations contained within the global economic model and how the inputs and structure of the model enable its customisation. It then described the Operational Expenditure (OPEX) model that was developed through activities undertaken within OPERA Work Package 6 (WP6) to better reflect the influence of Operation and Maintenance (O&M) activities on project economics. The OPEX model will be updated with data logged during the operational phases of the OPERA project. Inclusion of real sea operational data will improve the accuracy of the global economic model's estimates and therefore reduce risk. The inclusion of real sea data differentiates the global economic model from the previous state of the art in the Wave Energy Converter (WEC) economic evaluation.

Further development of the model is like to occur in the following areas:

- Provide ability to calculate Annual Energy Production (AEP) within the global economic model for different WECs,
- Include template to ease inclusion of alternative region's Industry by Industry (IxI) Input-Output (IO) tables for calculation of economic impacts and job creation,
- Increased detail on CAPEX cost centres and uncertainties,
- Inclusion of additional externalities in the SCOE calculation.

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ANNEX I: SCOE READY RECKONERS

DEADWEIGHT

Deadweight accounts for the activity that would have occurred in the regions were the project's spend not invested in the area [29]. For both Spanish and Scottish scenarios, Deadweight is set as zero. A Deadweight of zero indicates that the project's investment is additional to the baseline investment that would have occurred were the project not to have gone ahead, i.e. the investment that occurs as a result of the project does not prevent other activity that would have otherwise occurred.

A range of potential Deadweight Ready Reckoners are presented in Table 4.

TABLE 4: DEADWEIGHT READY RECKONER [30]

Level	Description	Displacement
None	All of the benefits are as a result of the intervention	0%
Low	The majority of the benefits are as a result of the intervention	25%
Medium	About half of the benefits are as a result of the intervention	50%
High	A high level of the outputs/outcomes are not as a result of the intervention	75%
Total Deadweight	None of the outputs/outcomes are as a result of the intervention	100%

LEAKAGE

Leakage accounts for, "the proportion of outputs that benefit those outside of the intervention target area or group [29]." Each of the OPERA project partners involved in undertaking activities within the cost centre blocks (highlighted in section 3.5.1) will indicate the regions where they anticipate their spend will be invested. They will indicate what percentage of the spend they envisage being invested in the target region (Basque Country and Orkney), the national region (Spain and Scotland) and in Europe. The percentage of spend not invested in a particular region is Leakage.

A range of potential leakage ready reckoners are presented in

Table 5.

TABLE 5: LEAKAGE READY RECKONER [30]

Level	Description	Displacement
None	All benefits go to the target area/ the target group	0%
Low	The majority of benefits go to the target area/ the target group	10%
Medium	A reasonably high proportion of the benefits will be retained within the target area/ the target group	25%
High	Many of the benefits will go outside the area of benefit/ outside the target group	50%
Very High	A substantial proportion of those benefiting will be outside of the area of benefit/ be non-target group members	75%
Total Leakage	None of the of the benefits got to members of the target/ area group	100%

DISPLACEMENT

Displacement is the, "proportion of intervention benefits accounted for by reduced benefits elsewhere in the target area" [29]. This will depend on the change in the market due to the output of the project (it is not expected that the increased electricity production due to the WEC arrays will affect other electricity producers) and on the capabilities of the existing suppliers within the area. For example, if due to limited resources, a supplier takes on work for the project and is therefore unable to work on other projects, this would result in a high level of displacement. If capacity was available due to less activity in the area due to economic conditions, then displacement would be low.

A range of potential displacement ready reckoners are presented in Table 6.

TABLE 6: DISPLACEMENT READY RECKONER [30]

Level	Description	Displacement
None	No other firms/demand affected	0%
Low	There are expected to be some displacement effects, although only to a limited extent	25%
Medium	About half of the activity would be displaced	50%
High	A high level of displacement is expected	75%
Total Displacement	All of the activity generated will be displaced	100%

SUBSTITUTION

Substitution accounts for firms changing their activities due to the project activity. It is similar to displacement except within a firm. For example, the potential of a long-term secure contract because of the WEC array's deployment may incentivise a firm to switch from manufacturing one item to another. This would have a knock on affect within the region. Substitution is frequently combined in the displacement ready reckoner figure.

A range of potential Substitution Ready Reckoners are presented in Table 7.

TABLE 7: SUBSTITUTION READY RECKONERS [30]

Level	Description	Displacement
None	No substitution takes place	0%
Low	There are expected to be some substitution effects, although relatively limited	25%
Medium	About half of the activity would be substituted	50%
High	A high level of substitution is expected to arise	75%
Total Substitution	All of the activity would be strongly affected by substitution	100%

ANNEX II: EFFECTS CALCULATION

Two types of effects exist. Only Type II effects are used in the OPERA global economic model. Type I effects account for the knock on impact of one industry's economic activity on the region's supply chain. Type II effects account for the increased economic activity of employees due to the project spend.

Both effects are calculated through Industry by Industry (IxI) Input-Output (IO) tables [31]. The first step in calculating the Type I effects is to obtain a Leontief type I matrix using the IxI IO table. The Leontief type I matrix shows, "how much of each industry's output is needed, in terms of direct, indirect and, in type II matrices, induced requirements, to produce one unit of a given industry's output" [31]. The Leontief type I matrix is calculated through equation (II.1).

$$L_I = (I - A_I)^{-1} \qquad \text{(II.1)}$$

L_I is the Leontief type I matrix, I is an identity matrix and A_I is the direct requirements matrix which is each cell of the IxI IO matrix divided by its column total.

The Type I effects, due to the production of one unit in a specific industry, are then obtained by summing the rows of the Leontief type I matrix in the column that corresponds to the specific industry. Different columns are summed depending on the cost centre, as different industries are engaged depending on the cost centre.

The first step in calculating the Type II effects is to obtain a Leontief type II matrix. This is similar to the procedure carried out to calculate the Leontief type I matrix, but an additional row and column is added to the direct requirements matrix (A_I in equation (1)). The additional row represents the, "income paid to households per unit of the output industries" [31], A_{HI}. The additional column represents the, "amount of industry required per unit total household income from all sources [31]," A_{IH}. See equation (II.2),

$$A_{II} = \begin{bmatrix} A_I & A_{IH} \\ A_{IH} & A_{HH} \end{bmatrix}. \qquad \text{(II.2)}$$

A_{II} is the direct requirements matrix used to calculate the Leontief type II matrix, A_I is the direct requirements matrix used in equation (II.1), A_{HH} is the "household expenditure per unit of exogenous household income"; this number is set to zero.

The additional column (A_{IH}) is normalised using the total household income from all sources instead of the total household final consumption expenditure figure obtained from the IxI IO table [31].

The Leontief type II matrix is calculated using equation (II.3),

$$L_{II} = (I - A_{II})^{-1}. \qquad \text{(II.3)}$$

The Type II effects due to the production of one unit in a specific industry are then obtained by summing the rows of the Leontief type II matrix in the column that corresponds to the specific industry. As before, different columns are summed depending on the cost centre as different industries are engaged for different cost centres.