WETFEET

D7.5 - LCA and socio-economic implications of large scale deployment of the proposed breakthroughs

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EXECUTIVE SUMMARY

This report presents Deliverable 7.5 of the WETFEET H2020 project: "Life-Cycle Carbon Analysis and Socio-economic Implications of Large Scale Deployment of the Proposed Breakthroughs". The aim of this deliverable is to assess the wider impact of the proposed wave farms, and variants (breakthroughs), by assessing the energy and carbon flows, macro-economics and social acceptance. This is carried out for locations in Scotland and Portugal, providing a detailed regional analysis of the wave farm impact and an isolation of the effect of breakthrough technologies applied. A conventional Life-Cycle Analysis (LCA) is used to compute energy and carbon flows, whilst national Input-Output (IO) models are developed to assess the macro-economic effects. An additional qualitative study is included assessing likely social impacts and acceptance. Both numerical models are coupled to the techno-economic model detailed in WETFEET D7.3, providing a comprehensive Techno-economic—LCA—IO model able to assess a wide range of outputs for a variety of technologies and locations.

This report details the methodology used for computing the LCA and IO models, whilst defining the variables used for exploration and those fixed for the analysis. Results relating to the LCA, IO for Scotland and IO for Portugal are provided separately; each of which assessing the reference case prior to exploring the influence of the proposed breakthroughs on the results.

In terms of energy and carbon, the LCA shows that the wave farm of OWC devices has a much lower carbon intensity than fossil fuels, yet has significantly worse carbon performance than more established renewable technologies. It is concluded that this is a result of having a low power rating relative to the material used for device manufacture and installation. It is also shown that a larger amount of energy and carbon is required for installation at the Leixoes site in Portugal, compared with Orkney, Scotland, yet over the lifetime of the project the overall benefit of the project installed in Portugal is higher. Due to similar available wave resource between locations, it is expected that this is a result of device tuning to the Leixoes site. It is found that the Negative Spring (NS) breakthrough provides the largest improvement in carbon and energy performance, whilst the Di-Elastomer Generator (DEG) and Survivability Submergence (SS) actually results in negative expected impact relative to the reference case.

Detailed macro-economic analysis for both locations highlights the large regional economic sector interdependency, showing that the proposed project stimulates output from all 29 aggregated sectors used for analysis. Sectors related to electrical equipment, manufacturing and water transport are expectedly associated with the largest demand and output. The reference case provides a peak of 293 jobs in Scotland during the combined installation and manufacture phase, with over 700 in Portugal for the same period. This increase is due to a much larger distance to port & shore, and a deeper water depth, requiring greater capital for the manufacture and installation of electrical and mooring cables. In terms of breakthroughs, survivability submergence as a strategy is associated with the largest jobs and GVA, yet this reflects poor micro-economic performance. This highlights the requirement to consider both micro and macro-economics to assess the overall value of a project.

Lastly, it is concluded that due to the progressive, environmentally conscious, attitude already present towards offshore renewable technologies in Orkney that social acceptance of the project will be very high. Although large-scale opposition is not expected in Leixoes, due to proximity to a major port significant opposition is to be expected from those with a stake in the fishing and transportation sectors.

The results presented highlight the large and wide-reaching benefits associated with the development of wave energy farms. The coupled model created to assess these effects, if developed further, has the potential to be a useful resource for the developing wave energy sector.

LIST OF ACCRONYMS

AEP	Annual Energy Production
CAPEX	Capital Expenditures
DE	Dielectric Elastomers
DEG	Dielectric Elastomer Generator
EAM	Enhanced Added-Mass
LCOE	Levelized Cost of Electricity
NS	Negative Spring
O&M	Operations and Maintenance
OPEX	Operational Expenditures
OWC	Oscillating Water Column
PTO	Power Take-Off
SCOE	Society's Cost of Electricity
TPL	Technology Performance Level
TRL	Technology Readiness Level
WEC	Wave Energy Converter
LCA	Life-Cycle Analysis
MRE	Marine Renewable Energy
IO	Input-Output

1. Introduction

1.1. Aims and motivation

The WETFEET project largely focuses on the technical design, testing and simulation of two WEC's: OWC and Symphony, with emphasis on assessing a number of proposed technical breakthroughs. To understand the overall benefit of the proposed WECs and associated breakthroughs, it is necessary to look beyond device performance and techno-economics. This deliverable aims to assess the wider impact of large-scale deployment of the proposed breakthroughs: determining the Life-Cycle Analysis (LCA) and socio-economic implications of the prospective wave farm variants over their life-time. The understanding of the embodied carbon and macro-economics of the wave farm developments will quantify the regional and global benefits of the proposed breakthroughs. The outcomes will help assess the wider impact of breakthroughs relative to each other, and to other competing energy technologies.

1.2. Scope of document

This document addresses both the LCA and socio-economic impact of large-scale deployment of a farm of OWC devices with various isolated breakthroughs applied. Portugal and Scotland are used as representative locations: providing real site characteristics and regional economic interdependencies associated with likely deployment locations. It was intended to complete the same analysis for the Symphony device as well, yet the late delivery of the techno-economic model (D7.3) required for this modelling work made this not possible. Key elements of the location-specific understanding gained through this work will, however, apply to both the OWC and Symphony devices.

The majority of the document describes the models applied and interpretation of the results. A conventional LCA is used to assess the energy and carbon performance, and an Input-Output (IO) model is used to quantify the socio-economic impacts. An additional qualitative assessment is offered discussing social impacts and acceptance of large-scale deployment. The breakthroughs which are referred to and studied are not described in this document, and the reader is referred to [1] [2] for detailed information.

The coupled techno-economic-LCA-IO model resulting from this work enables a comprehensive assessment of micro and macro-economic effects as well as energy and carbon flows associated with the prospective wave farm variants. There are an extremely high number of degrees of freedom in this model, and as such, to practically present useful information only a defined priority parameter space is explored, defined in Section 2.2. The remainder of the document is laid out as follows. Section 2 details the methodology, describing the links and dependency on the techno-economic model, D7.3 (2.1), and the overall approach used to carry out the LCA (2.3) and assess socio-economic implications (2.4). Corresponding results and interpretation for prospective farms of OWC devices are presented in Section 3 , focusing initially on the reference case (no breakthrough) prior to assessing the additional impact of breakthrough on the results. The expected social impacts and acceptance associated with the farms deployed at the two locations are discussed in Section 4. Additional discussion is offered in Section 5 prior to providing concluding remarks in Section 6.

2. Methodology

2.1. Link to techno-economic model

Both the LCA and IO models are linked to the techno-economic model detailed in WETFEET Deliverable D7.3. This extensive model considers a wide variety of parameters, enabling the assessment of various locations, device types, farm layouts, materials, vessels and other parameters. Although the number of considerations, categories, and variables associated with the model makes integration with the LCA and IO more challenging, both models were integrated to maximise realism and ensure consistent assumptions were applied throughout the WETFEET project.

The decision to create a coupled Techno-economic—LCA—IO model requires all CAPEX and OPEX entries to be associated with their embodied energy and carbon, whilst also requiring detailed categorisation for IO assessment of macro-economic effects. The inclusion of these 80+ entries, and the work required to obtain each of these values, results in a comprehensive assessment of the likely impacts. The resulting outputs should therefore be relatively realistic, yet as with any model are bound by limitations of the model and inherent assumptions. A detailed description of this techno-economic model is available in D7.3. The approach and associated assumptions relating specifically to the LCA and IO model are described in Sections 2.3 and 2.4.

2.2. Explored parameter space

There are many potential variables to explore if trying to comprehensively quantify the complex interdependencies between location, breakthrough type, materials, array layout etc. and their effect on the variety of resulting outputs. To simplify the analysis, and practically present the results, the total parameter space has been reduced and only a critical subset is explored. This subset, which applies to both the LCA and IO models is outlined below.

2.2.1. Location

As mentioned in Section 1.2, the number of locations to be assessed has been limited to two: Portugal and Scotland. For the LCA the actual deployment site is critical as the associated wave climate dominates the expected power output of the farm, and hence the energy and carbon performance. The distances to port and wave climate also influence the cost of installation and O&M costs, which influence both the LCA and IO models. It is therefore necessary to identify two prospective sites. These locations are detailed below, and have been chosen due to their associated wave climate and potential suitability as WEC farm deployment locations:

1. Leixoes, Portugal
    - Major port in the north of Portugal, located in Matosinhos near the city of Porto.
2. European Marine Energy Centre (EMEC), Orkney, Scotland, UK
    - Grid-connected test facility for wave and tidal energy devices

These two locations vary greatly on values of distances to shore, largest port and nearest O&M ports, as well as water depth, as shown in Table 1. In case of Leixoes, the distances from shore and ports are at least ten times larger compared to the EMEC site, and more than twice as deep at central farm location (106 m compared to 50 m). This suggests that the costs associated with water transport (especially in installation stage), electrical cables and mooring components (textiles and fabricated metal) will be significantly higher in case of Leixoes than EMEC. While the distance from shore to grid is more than twice as large for EMEC than Leixoes (5 km compared to 2 km), it stands to reason that the cabling used on shore is going to be cheaper than subsea cabling which is highly dependent on the distance of site to shore and water depth.

TABLE 1: SITE-SPECIFIC DISTANCES AND WATER DEPTHS AT LEIXOES, PORTUGAL AND EMEC, SCOTLAND

	Leixoes	EMEC	
Distance from nearest large port to site	30	3	km
Distance from nearest small O&M port to site	30	3	km
Distance from site to shore	30	2	km
Distance from shore to substation/grid	2	5	km
Water depth at central farm location	106	50	m

Contours describing the relative abundance of significant wave height, H_{m0}, and energy period, T_E for the two sites are shown in Figure 1. This demonstrates the differing nature of the two sites in terms of spread of likely sea state conditions. The mean values, however, are comparable, with the Leixoes site having mean values of H_{m0} and T_E of 2.0 m and 8.6 s, and EMEC 1.8 m and 8.8 s.

An interesting difference between the sites is evident when assessing the distance to port. EMEC, designed specifically to facilitate the deployment of marine renewable energy (MRE) devices, has a much smaller distance to a major port, and as such the costs, carbon and energy associated with installation will be significantly reduced. These differences in wave climate and port distance between the two locations will enable these factors to be indirectly assessed throughout the models.

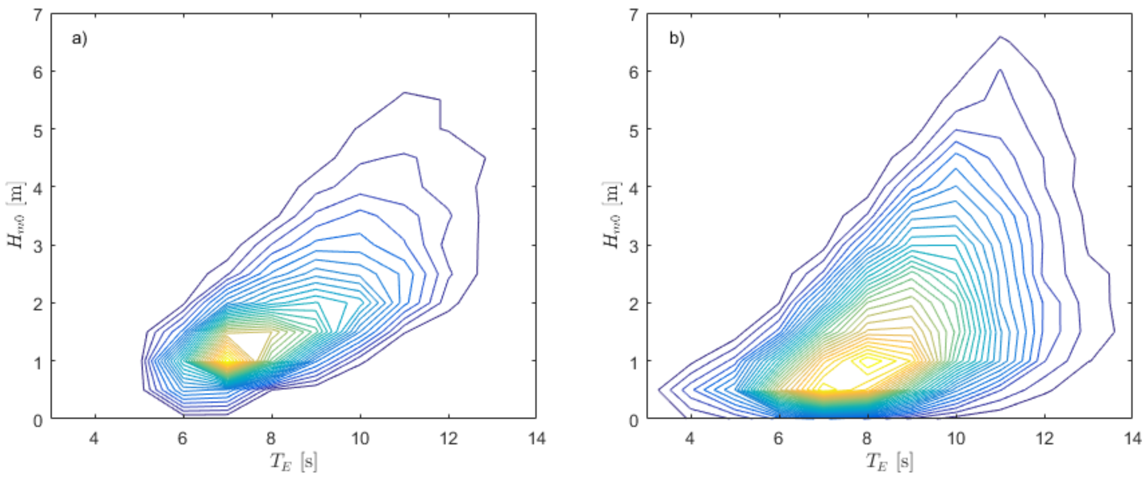

FIGURE 1: CONTOUR MAPS REPRESENTING RELATIVE ABUNDANCE OF SEA STATES WITH A GIVEN H_{m0} AND T_E. SHOWN FOR A) LEIXOES AND B) EMEC

2.2.2. WEC Design

The assessment of the breakthroughs is the focus of the WETFEET project, and as such all breakthroughs related to the WEC design need to be separately modelled and assessed. For the OWC there are 6 breakthroughs to be separately assessed relative to the reference case. These 7 cases are detailed in Table 1, and are well described in deliverable D2.1 The first 6 of these variants are assessed in this analysis, however, the Tetra-Radial Turbine (TRT) case (7) could not be accurately modelled due to the lack of an available power matrix at the time of completing the analysis.

TABLE 2: OWC WEC DESIGNS CORRESPONDING TO THE PROPOSED BREAKTHROUGHS. THE VARIANTS IN BLUE HAVE BEEN ASSESSED IN THIS DOCUMENT. SEE [1] FOR MORE INFORMATION.

Device Code	1. REF	2. EAM	3. NS	4. SS	5. SM	6. DEG	7. TRT
Full name	Reference case	Enhanced added mass	Negative spring	Survivability submergence	Shared moorings	Dielectric elastomer generator	Tetra-radial turbine

2.2.2.1. Materials

The masses and volumes of WEC substructures are determined by the breakthrough chosen, which are all assessed separately. The choice of materials, however, for both the main structure and ballast are variables in the techno-economic model. To reduce the number of parameters to explore these have been fixed for the LCA and IO analysis, with structural material and ballast set to be steel and concrete respectively.

2.2.3. Farm Design

2.2.3.1. Farm Size

To ensure consistency with the techno-economic assessment (D7.3), a fixed minimum farm size has been used throughout the analysis: 5MW. For the farm of OWC WECs this means arrays of 35 devices are considered.

2.2.3.2. Farm Configuration

MOORINGS

One of the isolated breakthroughs for the OWC is the implementation of shared mooring configurations for farms of WECs (see Table 1). For all other cases the three-point catenary mooring configuration shown in Figure 2 applies. Several shared mooring configurations for the OWC are implemented in the techno-economic model, however, to limit the number of variables only a single shared mooring configuration is considered for the LCA and IO models. This configuration, referred to as C in WETFEET deliverable D6.2 is shown in Figure 3.

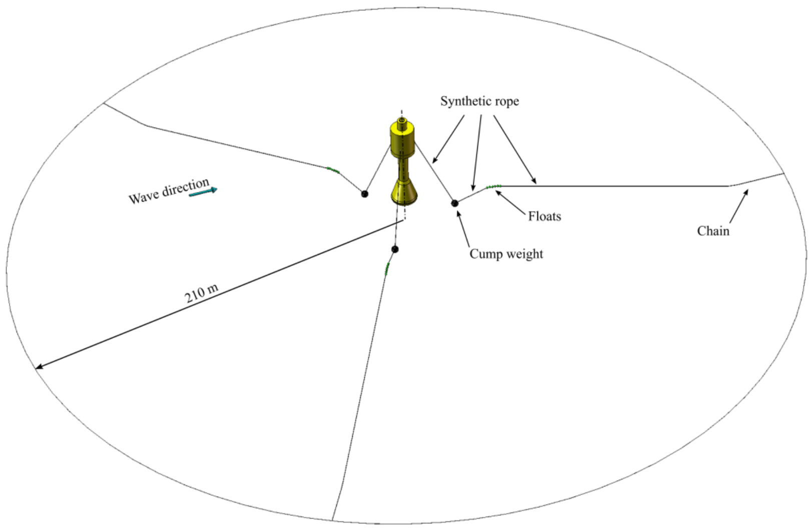

FIGURE 2: MOORING CONFIGURATION FOR OWC WEC

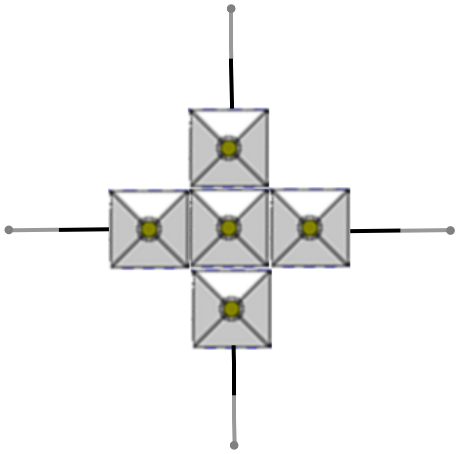

FIGURE 3: SHARED MOORING CONFIGURATION FOR OWC WEC. MOORING C USED FOR ANALYSIS, FROM D6.2

ELECTRICAL CONFIGURATION

Various electrical connection configurations have been implemented in the model. To reduce the number of variables considered, the electrical configuration has been fixed in this work. A star array has been chosen for this study, whereby each device has its own umbilical cable, and 'stars' of devices are grouped prior to connection to the offshore substation. This is illustrated further when detailing the methodology for the LCA in Figure 5.

FARM LAYOUT

As with the electrical and mooring configurations there are a variety of options for intra-array separations. To simplify the analysis only a single farm layout is assessed with 2 rows of devices. The distance between devices is set in the techno-economic model as just over 13 device diameters (which does not apply to shared mooring configurations) and has been used throughout.

FARM LIFETIME

Where relevant the assumed project lifetime is 20 years from when installation is complete.

2.3. Life-Cycle analysis

An LCA analysis typically consists of three phases, defined below:

1. **Goal and scope definition**
   Explicit statement and definition of the intended purpose and boundaries of the analysis.
2. **Inventory Analysis**
   Defining and calculating flows of inputs and outputs to and from the defined system. In this case the focus is on the net flow of energy and carbon.
3. **Impact assessment**
   Evaluating the significance of the inventory analysis. Typically involves classification and characterisation of inventory analysis outputs, and subsequent interpretation of the results.

The scope and system boundaries used in this work are described in Section 2.3.1, whilst the approach to inventory analysis is detailed in Section 2.3.2. The impact assessment is essentially presented for the Section 3.1.

2.3.1. Goal and scope definition

The goal and scope definition defines what precisely is being assessed, along with the system boundaries and assumptions inherent in the analysis. The goal of this LCA is to identify the embodied energy and carbon associated with the large-scale deployment of proposed breakthroughs, along with the energy and carbon payback and associated intensities. Hence, only carbon and energy flows need to be considered throughout.

The boundaries of the problem need the be large enough to properly represent the flows in and out of the defined system, but not too large as to be difficult to compute and assess. As the wave farms are relatively small, and consequently do not imply the construction of vessels, vehicles, and factories, these are omitted from the system boundaries. The system boundaries decided upon are depicted in Figure 4, incorporating the energy and carbon flows associated with fabrication, installation, O&M and decommissioning.

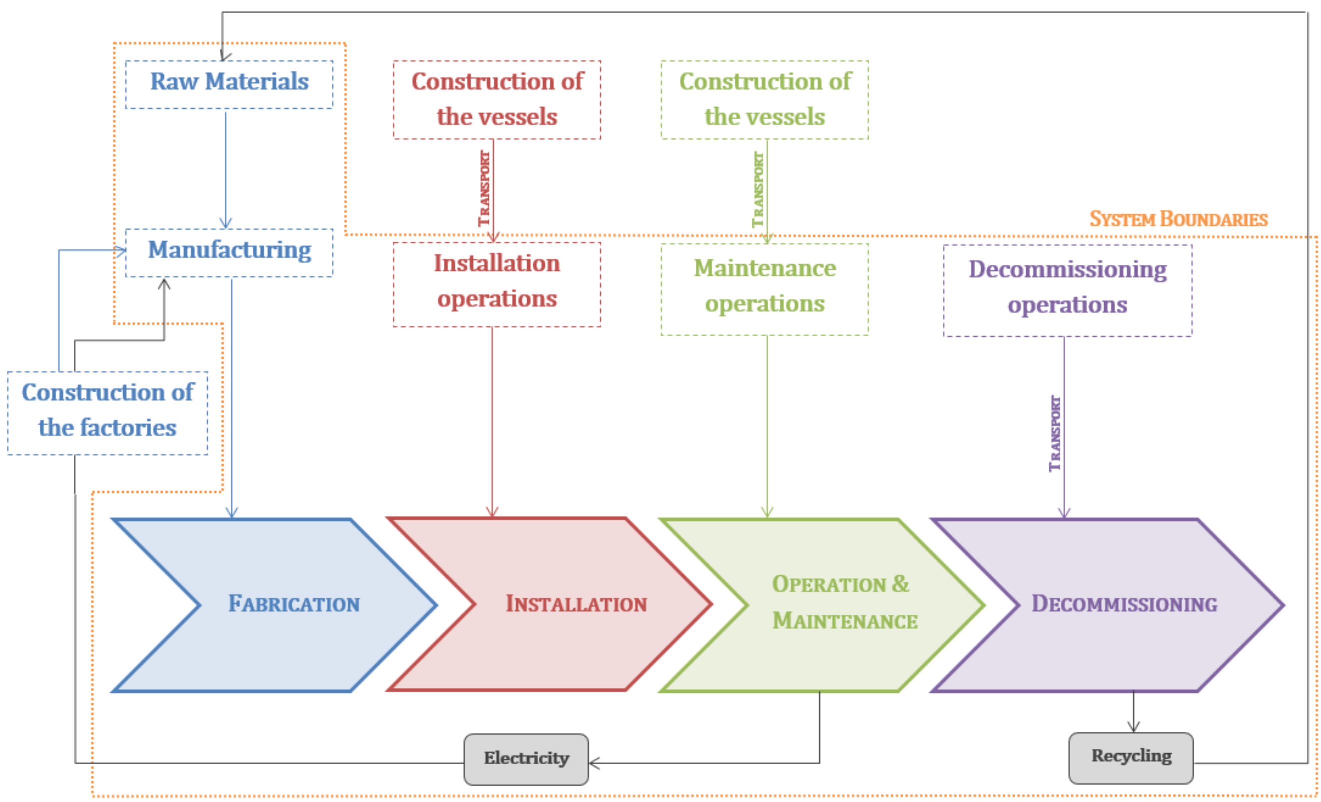

Figure 4: System boundaries for the LCA

2.3.2. Inventory analysis

To model the flows of energy and carbon both in and out of the defined system it is necessary to consider the following:

1. Materials
   a. Raw materials associated with the structure
   b. Manufacturing
   c. Recycling
2. Operations

a. Installation
b. O&M
i. Inspection
ii. Repairs
c. Decommissioning
3. Energy production

These three sections need to be dealt with in different ways. The materials require embodied carbon and energy associated with the production and manufacture of materials to be calculated, before accounting for the expected level of recycling to obtain net values. The energy and carbon flows associated with operations is largely attributed to expected fuel consumption of vessels used for installation and maintenance. The energy production, based on the device performance and wave climate, provides values of energy flow and associated `displaced' carbon out of the system boundary. The methodology used to compute the flows for these three areas are detailed below.

2.3.2.1. Raw material breakdown

MAIN DEVICE

The main structure (or substructures) is broken down into component materials: steel, concrete, and composite. The embodied carbon and energy associated with the required masses of these materials can be obtained from available databases, such as the Bath Inventory of Carbon and Energy (ICE)[3] used in this study. Where no values are available in the database for composites, the mass ratios of component materials are used to obtain approximate embodied carbon and energy.

The PTO is a relatively small proportion of the overall weight and embodied energy/carbon, and therefore has been assumed to be steel for simplicity of the analysis.

MOORINGS & ANCHORS

The moorings are specified in the techno-economic model as lengths of rope, light and heavy chain. Relative lengths vary depending on the breakthrough being analysed and the chosen array configuration. To calculate the embodied energy and carbon it is necessary to choose appropriate materials, which have not yet been defined. All chain sections and anchors are assumed to be made of steel, and rope is taken to be synthetic polypropylene.

ELECTRICAL INFRASTRUCTURE

The electrical infrastructure is quite complex, and consists of a variety of electrical cables, several junction boxes, along with one offshore substation and export cable. Based on the assumed array configuration described in Section 2.2.3.2, 135 devices are connected to each junction box via umbilical and dynamic seabed cables. The 7 junction boxes are connected to the offshore substation utilising static inter-array cables. This is depicted in Figure 5.

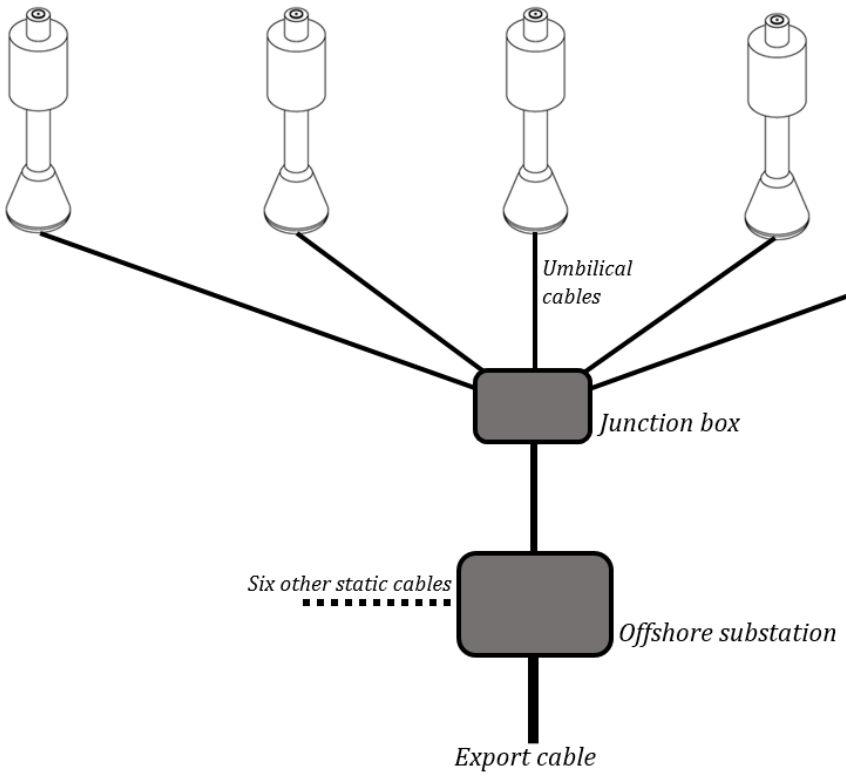

FIGURE 5: DIAGRAM DEPICTING SUB-SEA CABLE CONFIGURATION FOR A FARM OF OWC DEVICES, UTILISING A STAR-CONFIGURATION FOR UMBILICAL CABLES

To calculate the embodied carbon and energy in the extensive offshore cable network the composition of the cables needs to be assumed. Based on industry standard submarine power cables [4] the composition of all electrical subsea cables is assumed to have the cross-section depicted in Figure 6. The differing power requirements of the electrical network determine the local required cable diameters. The diameters calculated, in combination with the lengths computed in the model, enable the total masses of each component cable material to be identified, along with the associated energy and carbon.

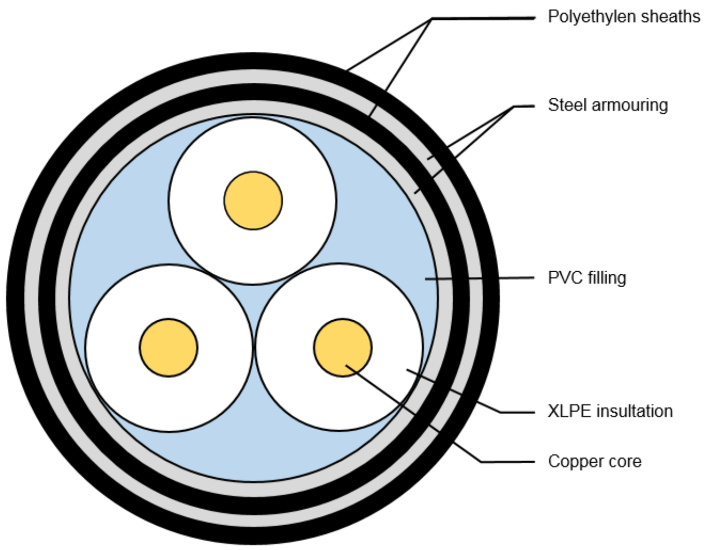

FIGURE 6: CROSS-SECTION OF A REPRESENTATIVE TRIPLE CORE DOUBLE-ARMOURED SUB-SEA CABLE

In addition to the energy and carbon embodied in the cables, those associated with the offshore substation and junction boxes are also estimated. This provides a total estimate for the raw materials used for electrical infrastructure.

MANUFACTURING

Manufacturing processes also incur energy and carbon costs; however, this is expected to be a small proportion of the total embodied carbon and energy. From [5] the manufacturing is expected to be 4% of that associated with the raw materials. Other studies, such as [6] suggest values less than this (1.82% in this case), however, 4% has been used to ensure the value used is conservative.

RECYCLING

Recycling reduces the net energy and carbon flows into the system boundaries and hence those attributed to the prospective wave farm developments. For the purpose of the analysis the energy and carbon associated with secondary steel is used; implying 100% recycled steel is used for the project. For other materials zero recycling is assumed.

2.3.2.2. Operations

INSTALLATION

As detailed in WETEET D7.1, to install the devices, moorings and cables; four vessels, two ROVs and one crane are required. As part of the logistics in the techno-economic model (D7.3) the distances and number of operations are computed. To enable calculation of the carbon and energy, the energy density and carbon emissions of diesel are required, along with the fuel consumption associated with each operation. For each vessel (and the crane) estimates are made on the fuel consumption of each operation: loading, transportation etc. This is based on the expected vessel speed of the operation relative to maximum speed and associated fuel consumption.

O&M

The O&M is carried out in a similar manner to the installation, computing the expected fuel consumption associated with each operation. There are two major differences to consider. The first is that the vessels required are different as most O&M operations only require small vessels. The second is that the frequency of operations is a strong function of the expected failure rates which in turn is heavily influenced by the WEC design breakthrough applied. Considering the vessel requirements and frequency of planned inspections and reactive repairs, the same methodology is applied to obtain energy and carbon flows as that described for installation.

DECOMISSIONING

The decommissioning operations are assumed to be the inverse of the installation, and hence are assumed to be have the same associated energy and carbon. Many studies [7][8] demonstrate that decommissioning typically has lower environmental cost than installation, however due to limited information they have been assumed equal for this study, providing conservative estimations.

2.3.2.3. Energy production

The energy production is readily computed using a combination of the scatter diagram of sea state conditions, and power matrix corresponding to the device performance. The relative abundance of H_{m0} and T_E along with the expected power output provides mean power which can be readily scaled to give the theoretical annual energy production (AEP). To predict actual AEP, availability and losses need to be considered. Availability is assumed to be 96% (D7.3). Intra-array and electrical transmission losses are incorporated in the model enables calculation of the approximate electrical power injected into the grid.

Including energy and carbon flows with the materials and manufacturing, operations and energy production allows net flows to be obtained for the system for each of the breakthroughs. Categorisation and analysis of these flows are carried out in Sections 3.1.

2.4. Input-Output Model

Input–Output (IO) modelling is a quantitative method of macro-economic analysis, considering interdependencies between different branches of the economy. This modelling approach enables the wider economic benefit to a specified region to be assessed, based on knowledge of direct sectoral spend along with relevant multipliers accounting for the inter-relationships between economic sectors. Estimates are obtained for the number of created jobs and the total Gross Added Value (GVA) associated with the proposed project. For this work, IO modelling is utilized to quantify and understand the effects of the installment of proposed wave farms on Scottish and Portuguese economies.

IO modelling, as applied here, relies on a few assumptions, outlined below:

- The general equilibrium is maintained at all times of the project's duration.
- The price of goods is assumed to be constant throughout the project's duration.
- The overall market status is assumed to be complete for the whole project's duration.

Different levels of economic interdependencies can be considered when IO modelling, which are classified into Type I and Type II effects. The first of which incorporates the direct and indirect effects from the project spend, whilst Type II considers the direct, indirect, and induced effects resulting from household spending associated with the direct and indirect spend. For this model Type II multiplier effects are considered as these values give a better indication of the total macro-economic benefit of the proposed projects.

The model is created in five stages, which are expanded further in the following sections:

1. **Allocating CAPEX and OPEX expenditure from Techno-economic model to regional classification**

The coupled techno-economic model (D7.3) provides detailed CAPEX and OPEX expenditure throughout the project lifecycle stages. In order to implement the IO model, these entries need to be allocated to recognized regional classes, where interdependencies on other economic sectors are reported e.g. Standard Industrial Classes (SIC) 2007 [9].

2. **Creating grouped, simplified, industry by industry matrices**

The regional classification covers an extensive range of industries, and as such require aggregation to provide a clearer, easier understanding of the modelling outputs. For this work, regional classes have been aggregated into less than thirty classes. These groups have been used for creation of new industry by industry (IxI) matrices, describing the aggregated sector interdependencies.

3. **Applying Ready Reckoners**

Ready reckoners are required to compute the direct net spend in each of the cost centers, reducing effective expenditure to account for deadweight, leakage, substitution and displacement [10]. This enables more realistic attribution of macro-economic benefits to be associated with the project, ensuring these are not over-estimated.

4. Simulating Time-series of expenditure

In order to assess the time varying nature of project-induced macro-economic effects, the time-series of direct expenditure in each of the cost centers needs to be computed. This must include the ready reckoners identified in **3** and provide the direct output of sectors used to compute indirect and induced outputs, jobs and GVA. To do this the project is split into key stages (Manufacture—Installation—Operation—Decommissioning) and expenditure apportioned accordingly.

5. Computing the IO model

Once time-series of expenditure in each of the aggregated cost centers, incorporating ready reckoners, are computed it is possible to carry out the IO modelling. This involves the calculation of indirect and induced effects from the expenditure, along with an estimation of jobs created and GVA. Due to computing time-varying expenditure it is possible to observe the macro-economic effects over the differing life-cycle stages of the project.

The methodology of expenditure allocation for CAPEX/OPEX entries to regional classes is described in section 2.4.1, with the aggregation of these classes explained in section 2.4.2. The approach to incorporating Ready Reckoners is discussed in section 2.4.3. Time-series of net expenditure is detailed in section 2.4.4. while the IO modelling, including GVA and job creation calculations described in 2.4.5.

2.4.1. Classifying Entries

As the matrices which describe sector inter-dependency use standard classes, it is required that all project expenditure be allocated to these classes. To achieve this, each CAPEX and OPEX entry has been separated into the differing associated materials and services, and costs allocated to the most appropriate classes.

The attribution to classes for CAPEX and OPEX has been done by detailed assessment identifying the industry most influenced by the cost entry. In some cases, this means attributing costs between multiple industries by the expected relative influence. Summing total expenditure in each class provides indication as to the key sectors being shocked, and hence which ones should be kept as separate classes, and which can be aggregated to simplify the analysis and presentation of results.

2.4.2. Aggregation

Once key industrial sectors have been identified in the classification procedure, a process of aggregation can be carried out on those sectors of reduced interest. For this model the process resulted in 29 groups, clustered from the original SIC (2007) list of 98 separate industries. This has been carried out by identifying common characteristics e.g. the aggregated category “Food and Drink processing” encompasses industries such as dairy, meat and wine. The resulting aggregated groups are presented in Table 3, where sectors without aggregation are interpreted as those of most interest to the study.

TABLE 3: GROUPED SECTOR CLASSIFICATION

Chemicals	19. - 20.
Metal and non-metal goods	15. - 18.
Water transport	50.
Other manufacturing	21. - 24., 31. - 32.
Water	36. - 37.
Construction	41. - 43., 81
Distibution and other transport	49., 51. - 52.
Communications, finance and business	61. - 64., 66. - 68., 82.
Education, public and other services	53. - 60., 73. - 75., 78. - 80., 84. - 97.
Coal, Oil & Gas extraction	05. - 0.8.
Tobacco	13.
Gas & Electricity	35.
Wholesale & Retail	45. - 47.
Textiles	13.
Fabricated metal	25.
Electrical equipment	26. - 27.
Machinery & equipment	28.
Motor Vehicles	29.
Other transport equipment	30.
Repair & maintenance	33.
Insurance & pensions	65.
Legal activities	69.
Architectural services etc	70. - 72.
Rental and leasing services	77.

Once the aggregated groups have been formulated, it is necessary to use these new classes to create grouped industry by industry (IxI) matrices, describing the inter-dependency between defined aggregated groups. The same methodology needs to be applied to compute aggregated expenditure, and updated values of multipliers corresponding to the new classes.

2.4.3. Ready Reckoners

Ready reckoners are required to compute the net spend in each of the grouped cost centres for the area of interest. These additionalities contain information that try to account for the extent the project is directly responsible for the influence on the economy. Referring to [10] for guidance, the aforementioned additionalities can be summarized as follows:

1. **Deadweight**
   Gross direct effect of the reference case, gauging the rough estimate of benefits of the project that would have happened in the national economy in question. It includes the possibility of economy changing without the project ever occurring (100% deadweight) or all of the effects being directly a result of the project taking place (0% deadweight).
2. **Displacement**
   Ratio of intervention benefits accounted for to reduced profits in other parts of the target area. This can be understood as the way the companies changed due to the project's existence e.g. moving away from one part of the target area to another due to the other being more financially profitable at that point. Depending on the amount of movement the displacement effect is expressed as a percentage as well.
3. **Leakage**
   Proportion of outputs benefiting outside the intended target area/industry, which incorporates the fact that certain outputs will impact the sources not taken into consideration of a study e.g. the cars or ships used may belong to another country's manufacture.
4. **Substitution**

Unlike displacement, substitution is a ratio of actual benefits accounted for to the reduced ones elsewhere, meaning that it includes the previously missed benefits. This additionality describes e.g. the fact that some vocations will be filled upon firing a previous employee, so while the job count increased, the actual value of jobs in place stays the same. This is particularly important for the operational stage, since the sheer span of time suggests possible substitutions.

The estimation of the total net spend in each cost centre is then calculated by:

$$Y = [GI \times (1 - L) \times (1 - Dp) \times (1 - S) \times (1 - De) \times M]$$

where Y is the net sector demand, GI is gross impact, M is a multiplier while Ready Reckoners are Leakage (L), Displacement (Dp), Deadweight (De) and Substitution (S).

The Ready Reckoners implemented for Scotland and Portugal can be found in Table 4. The values of which, have been based on the following assumptions:

1. The local economies do not change by a significant margin if the project is not introduced (Deadweight: 0%)
2. The local economies may use vehicles or materials manufactured by organizations outside a country to a degree (Leakage of 50%, aside from motor vehicles where the value is closer to 80% due to main manufacturers being based elsewhere) but the manpower, brainpower and vessels used are assumed to be all of internal market (Leakage: 0%)
3. The companies are assumed to mostly stay within their area of expertise, which a small possibility of alteration in case of construction and vehicles areas, which might requalify for this project (Displacement: 25%)
4. Substitution may occur during operational and installation stages due to the nature of physical labour and duration of the stages in question (Substitution: 25% with notable exception of construction where increased risk of accident may cause increased changeover of 50%)

TABLE 4: READY RECKONERS ASSUMED FOR SCOTLAND AND PORTUGAL

	Ready Reckoners			
	Deadweight	Leakage	Displacement	Substitution
Textiles	-	0.50	-	-
Cement lime & plaster	-	0.50	-	-
Fabricated metal	-	0.50	-	-
Electrical equipment	-	0.50	-	-
Machinery & equipment	-	0.50	-	-
Motor Vehicles	-	0.80	0.25	0.25
Other transport equipment	-	-	-	-
Repair & maintenance	-	-	-	-
Construction	-	-	0.25	0.50
Water transport	-	-	-	0.20
Insurance & pensions	-	-	-	-
Legal activities	-	-	-	-
Architectural services etc	-	-	-	-
Rental and leasing services	-	-	-	-

2.4.4. Simulating time-series of expenditure

The project has been divided into four different stages: manufacturing, installation, operation and decommissioning. While the latter two stages are assumed to be exclusive, the manufacturing and

installation stages are modelled as overlapping. Theses stages are estimated to last 3, 2, 20 and 1 year respectively, with installation commencing after 1 year of manufacturing.

To simulate the time-series effectively, the classified CAPEX/OPEX entries are allocated to the 4 phases, and divided by the respective number of phase years to compute the annual direct output for the aggregated sectors. Incorporating ready reckoners enables the direct output to be estimated for our regions of interest, which then feed into the input-output model to provide annual wider macro-economic effects.

2.4.5. Input-output modelling

The methodology described in Sections 2.4.1 to 2.4.4 provides the final demand, Y, of the aggregated sectors, j, as appropriate for the region of interest. The IO model enables the wider effect of this spend to be assessed considering the multiplier effect resulting from sector interdependency. These multiplier effects can be split in two categories:

1. Supply linked – due to companies' supply chain. Sometimes referred as **indirect** multiplier.
2. Income linked – due to expenditure from people whose income is supplied from the project. Sometimes called **induced** multiplier.

Type II incorporates both effects, whilst Type I only incorporates indirect multiplier effects. Type II multiplier effects are considered in this work to fully account for the macro-economic benefit of the wave farms; incorporating direct, indirect and induced effects on sector output, jobs and GVA.

2.4.5.1. Type II Sector Output

The basic principle of computing IO models is that developed by Leontief [11], in that sectoral outputs can be linked to final demand via the well-known matrix equation:

$$X = [I - A_I]^{-1}Y$$

where X is the sectoral outputs and Y is the demand. The A_I matrix (Type I) is essentially the normalised equivalent of the IxI matrix developed for the aggregated groups. For Type I multipliers $A_{i,j}$ describes the relative amount of sector i required to create 1 unit of output for sector j.

For Type II, the effects of households also need to be considered, which can be formally described as:

$$A_{II} = \begin{bmatrix} A_I & A_{IH} \\ A_{HI} & 0 \end{bmatrix}$$

where A_I is the Type I matrix, A_{IH} is the amount of industry i required per unit of household income, and A_{HI} is the compensation of employees per unit of output of sector i. Type II sectoral outputs can then be calculated by:

$$X = [I - A_{II}]^{-1}Y$$

Where $L = [I - A_{II}]^{-1}$ is commonly referred to as the Type II inverse Leontief matrix.

2.4.5.2. Type II Employment and GVA

Type II GVA and employment can be computed using the following equations [12]:

$$J_j = Y_j E_j$$

$$GVA_j = Y_j G_j$$

$$E_j = \sum_i w_i L_{ij}$$

$$G_j = \sum_i g_i L_{ij}$$

where w_i is the Full Time Equivalent (FTE) employment for industry i divided by the column total of total output at basic prices, and g_i is the GVA for industry i divided by the column total. E_j represents the total impact on employment throughout the economy resulting from a unit change in final demand of industry j, and G_j the GVA equivalent.

E_j and G_j are commonly referred to as the employment effect and GVA effect. These must be calculated for the aggregated groups defined in Table 5. As an example, for the Scottish economy the calculated effects are shown in Table 3. It is interesting to note the widely differing values for employment, with some sectors being associated with stimulating over 4 times the number of jobs per unit demand.

TABLE 5: GROUPED TYPE II GVA AND EMPLOYMENT EFFECTS FOR SCOTLAND

SIC	↓ Industry group ↓	Employment effect	GVA effect
38. - 39.	Waste, remediation & management	10.20	0.71
01. - 03.	Agriculture, forestry and fishing	19.56	0.76
09.	Other mining and quarrying	11.15	0.87
10. - 11.	Food and drinks processing	11.10	0.61
14.	Clothing	13.40	0.69
19. - 20.	Chemicals	10.15	0.64
15. - 18.	Metal and non-metal goods	11.73	0.62
50.	Water transport	10.18	0.72
21. - 24., 31.	Other manufacturing	11.13	0.72
36. - 37.	Water	6.16	0.93
41. - 43., 81	Construction	24.37	0.90
49., 51. - 52.	Distibution and other transport	13.46	0.79
61. - 64., 66.	Communications, finance and business	14.38	0.90
53. - 60., 73.	Education, public and other services	23.03	0.94
05. - 0.8.	Coal, Oil & Gas extraction	6.91	0.69
12.	Tobacco	-	-
35.	Gas & Electricity	5.11	0.56
45. - 47.	Wholesale & Retail	18.47	0.90
13.	Textiles	9.76	0.80
25.	Fabricated metal	13.34	0.81
26. - 27.	Electrical equipment	9.71	0.69
28.	Machinery & equipment	11.17	0.73
29.	Motor Vehicles	8.21	0.59
30.	Other transport equipment	9.73	0.64
33.	Repair & maintenance	12.59	0.89
65.	Insurance & pensions	6.70	0.69
69.	Legal activities	20.23	1.01
70. - 72.	Architectural services etc	19.54	0.91
77.	Rental and leasing services	11.00	0.85

2.5. Qualitative Study on Social Impacts and Acceptance

To assess likely social impacts and acceptance of the wave farm(s) it is necessary to look beyond GVA and employment statistics; although these will have significant influence. An additional qualitative study is therefore carried out. The approach taken has been to review literature on social impact studies focusing on marine developments in analogous areas, whilst additionally profiling the specific locations of the proposed deployments. This will enable location specific factors to be accounted for which will influence social impacts, opinions and acceptance of these proposed projects. The outputs of this study are presented in Section 4.

3. LCA & Socio-Economic Impact of a farm of OWC Devices

3.1. Life-Cycle Analysis

The LCA has been carried out using the methodology outlined at Section 2.3. Results are presented and discussed for the baseline case in Section 3.1.1, prior to exploring the additional effect of breakthrough on the net energy and carbon flows associated with the farm of OWC devices in Section 3.1.2.

3.1.1. Baseline Results

The baseline LCA results for the farm of OWCs are detailed in this section, for both Portugal and Scotland. Energy and carbon associated with different materials is covered in 3.1.1.1, with assessment of different life cycle stages in 3.1.1.2. Section 3.1.1.3 assesses the carbon intensities of the proposed farm relative to other energy sources, before 3.1.1.4 presents estimates of the energy and carbon flows over the project lifecycle.

3.1.1.1. Material Breakdown

Ratios of embodied energy and carbon in materials are only weakly correlated to location; affecting the mooring and cable lengths. The differences for the two locations analysed, EMEC and Leixoes, are relatively small and in relative percentage terms remain constant (to integer values). As such, only the Leixoes example is presented below in Figure 7.

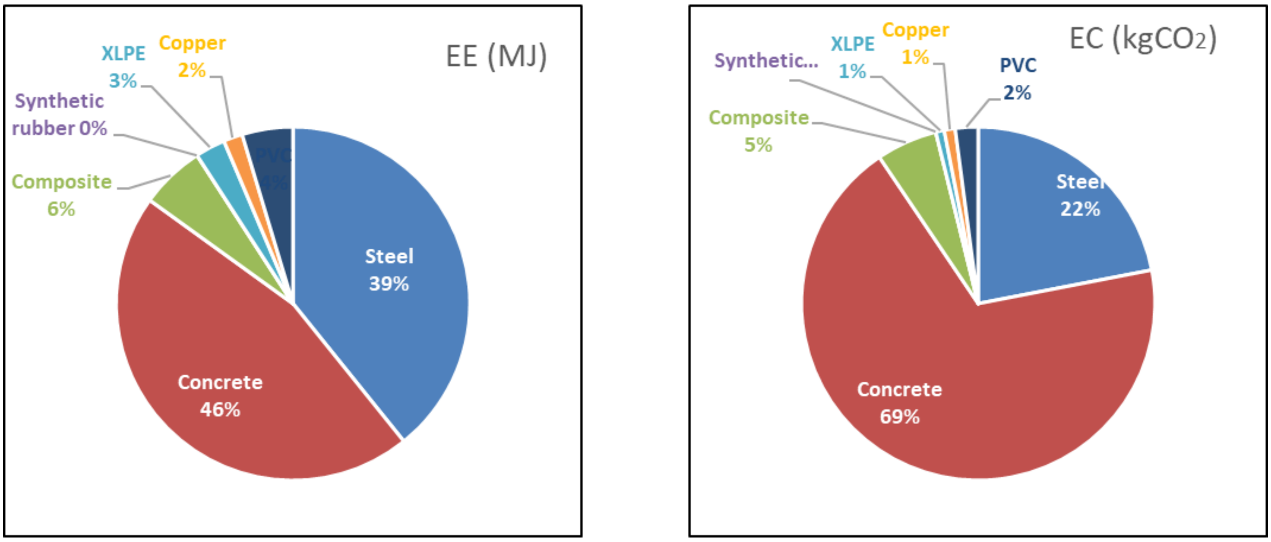

FIGURE 7: EMBODIED ENERGY (LEFT) AND CARBON (RIGHT) IN THE FARM OF OWC DEVICES, CATEGORISED BY MATERIAL

Assessing Figure 7, two findings are apparent. The first is that the embodied energy and carbon associated with materials are dominated by the concrete and steel used, with the combination accounting for 85% of embodied energy and 91% of embodied CO_2. The second is that concrete makes up the vast majority of the CO_2 associated with materials, accounting for over two thirds of total emissions. This is an interesting finding, as concrete is typically used to reduce cost yet incurs significantly higher environmental costs than alternative materials.

3.1.1.2. Life-Cycle Stages

The total embodied energy and carbon throughout key project life-cycle stages is presented in Figure 8, for both the Leixoes and EMEC sites. The distribution of associated energy and carbon flows is largely as expected, with materials and manufacturing accounting for the majority. This ties up with previous

work on marine renewable technologies [7], reiterating that the largest environmental savings can be made with changes to the main WEC design and structure.

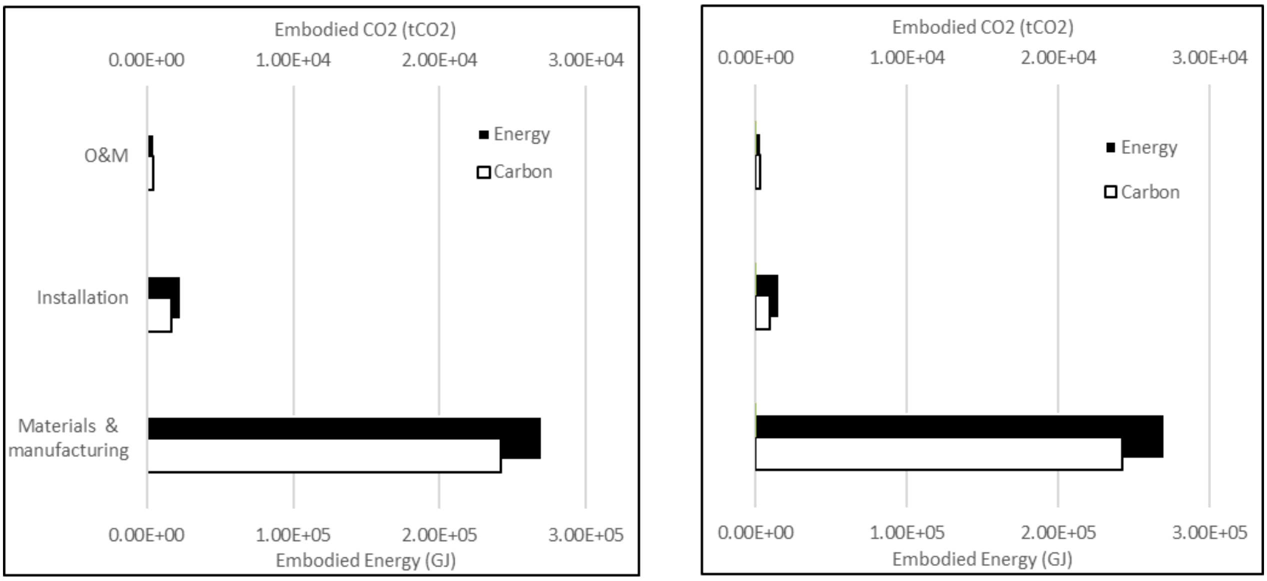

FIGURE 8: EMBODIED ENERGY AND CARBON FOR BASELINE CASE IN LEIXOES (LEFT) AND EMEC (RIGHT) RESPECTIVELY

As expected, due to the larger distance to port, the Leixoes site has larger associated energy and carbon with both installation and O&M, whilst materials and manufacturing remain equivalent.

3.1.1.3. Relative Carbon Intensities

As this section aims to assess the baseline case it is relevant to compare the proposed WEC farm of OWC devices to other widely used energy technologies. A convenient way to assess this is by utilising carbon intensity; defining the ratio of lifetime CO_2 emissions to expected lifetime energy production. The results of this are shown in Figure 9, displaying values for the OWC farm at both EMEC and Leixoes, compared with other sources derived from [13]. It is evident from this analysis, that although the OWC farm has significantly lower carbon intensity than fossil-fuel based energy sources, it has significantly higher values than those of more established renewable technologies. This is largely due to the proposed WEC fam consisting of a small number of devices with relatively low power rating. There is hence a relatively low power output for the amount of material used, which dominates the embodied CO_2.

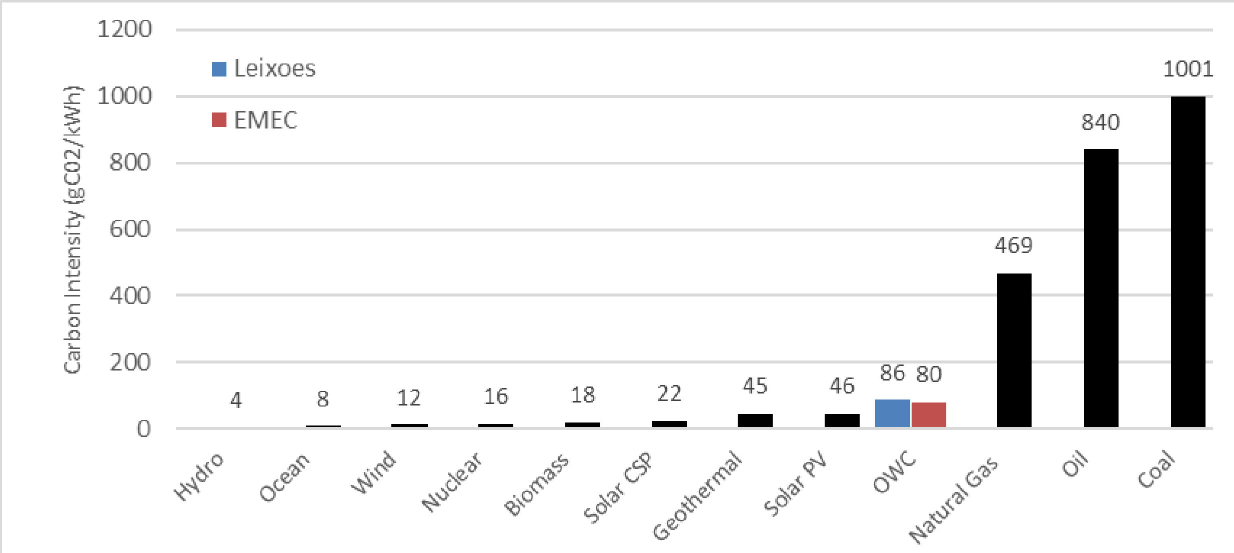

FIGURE 9: RELATIVE CARBON INTENSITIES OF THE PROPOSED OWC FARM IN PORTUGAL AND SCOTLAND, COMPARED WITH OTHER ELECTRICITY GENERATION. INFORMATION USED FROM [13]

3.1.1.4. Energy and Carbon Payback

The carbon intensities presented in Figure 9 represent, in a sense, the carbon performance of the proposed OWC farm compared to other technologies. It does not, however, indicate which projects have net negative flows of carbon and energy, and what these net figures are. To assess this, the cumulative energy and carbon values can be assessed as a function of project year. This is relatively simple for energy used/produced yet for carbon flows the location-dependent energy mix must be considered. Carbon `displaced' must be calculated with reference to the current sources of electricity in the countries being considered, assessing the relative use and corresponding carbon intensities (Figure 9) of each of the sources. The energy mix for the UK [14] and Portugal [15] are displayed, as of 2016. It is assumed these relative values are still representative.

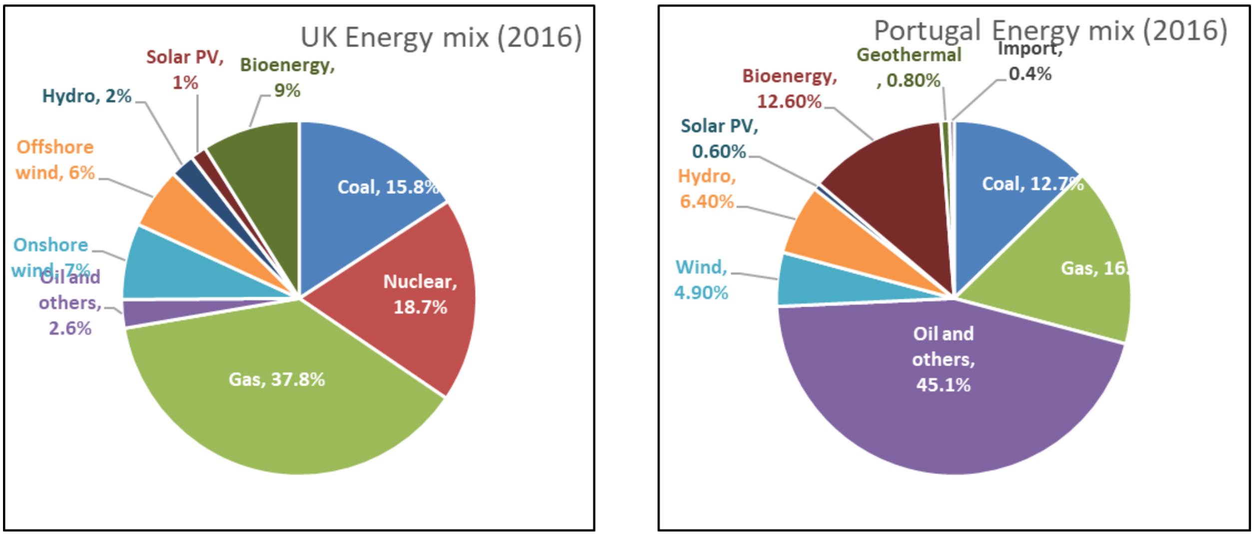

FIGURE 10: ENERGY MIX FOR UK (LEFT) AND PORTUGAL (RIGHT) BASED ON 2016 FIGURES [14] [15]

From Figure 10, and noting the carbon intensities in Figure 9, it is evident that Portugal has a much larger amount of `dirtier' energy sources; namely oil and coal. The proposed farm of OWC devices will therefore displace a larger amount of carbon if installed in Portugal per unit of electricity produced.

Computing the cumulative year-on-year carbon and energy flows for the baseline case of OWC devices installed in EMEC and Leixoes yields the results presented in Figure 11. The expected project end date (20 years) is indicated by the red dashed line, and values at this point are the estimated net energy and carbon flows for the proposed project (e.g. to compute carbon intensities). With the convention used for this graph, this corresponds to the project being a net displacer of carbon and producer of electricity, as expected. Examining Figure 11, it is evident that the farm of OWC devices is producing fractionally more power at the Leixoes site, yet this corresponds to a significantly larger amount of displaced CO_2, as would be expected from the Portuguese energy mix displayed Figure 10. These final energy and carbon flows mean that, despite the Leixoes project having a higher carbon intensity, the net positive impact of the farm is greater when deployed here. Due to similar available wave resource between locations, it is expected that this is may be partly a result of device tuning to the Portuguese site, and similar performance may be gained for the EMEC site if tuned for this location.

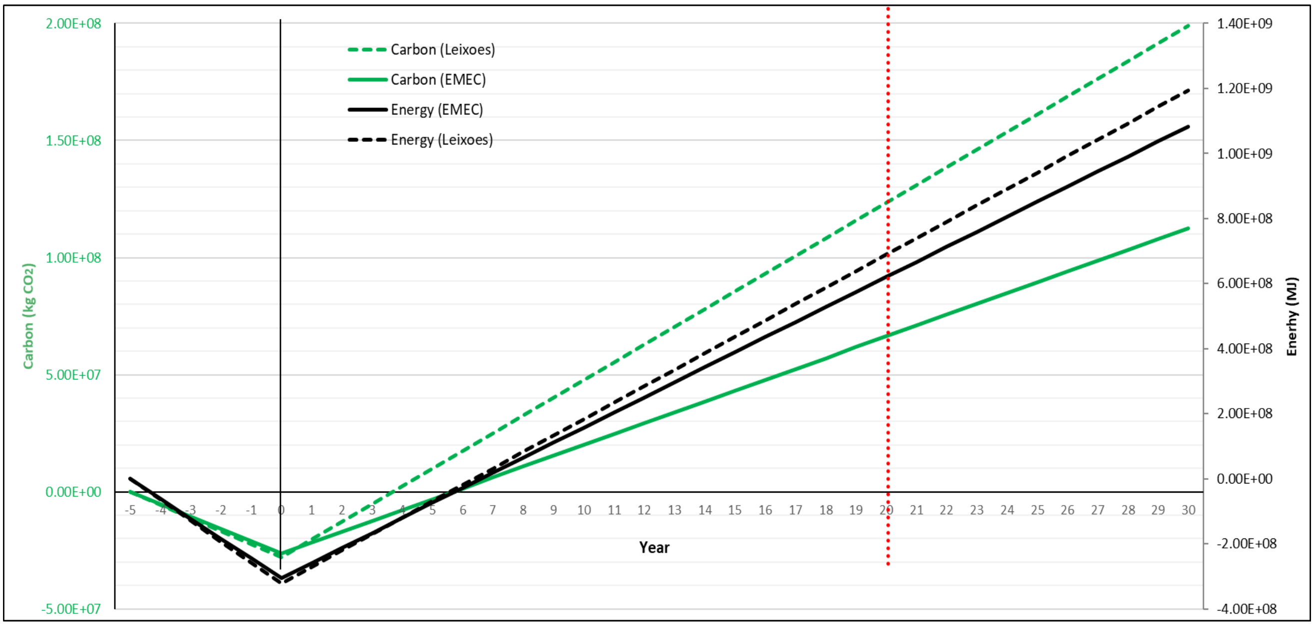

FIGURE 11: CUMULATIVE ENERGY AND CARBON FLOWS FOR OWC FARMS INSTALLED IN EMEC AND LEIXOES

3.1.2. Influence of Breakthroughs

This section expands on the baseline results presented in Section 3.1 to explore the influence of breakthroughs on the energy and carbon flows associated with the proposed OWC farms. The performance at the two locations, EMEC and Leixoes, is assessed for all breakthrough variants. These breakthroughs are referred to by shortened references in this section, corresponding to those detailed in Table 2.

3.1.2.1. Material Breakdown

The breakdown of embodied CO_2 and energy in materials, for each of the breakthroughs, is presented in Figure 11 for Leixoes and Figure 12 for EMEC. It is evident the negative spring (NS) breakthrough is associated with the smallest embodied values for CO_2 and energy, at both sites, due to the significant reduction in structural steel and concrete required for manufacture. Analogous savings are observed for the enhanced added mass (EAM) case, but to a lesser extent. It is evident that the other technical breakthroughs do not significantly improve the embodied carbon and energy in materials, when assessed for either of the two sites.

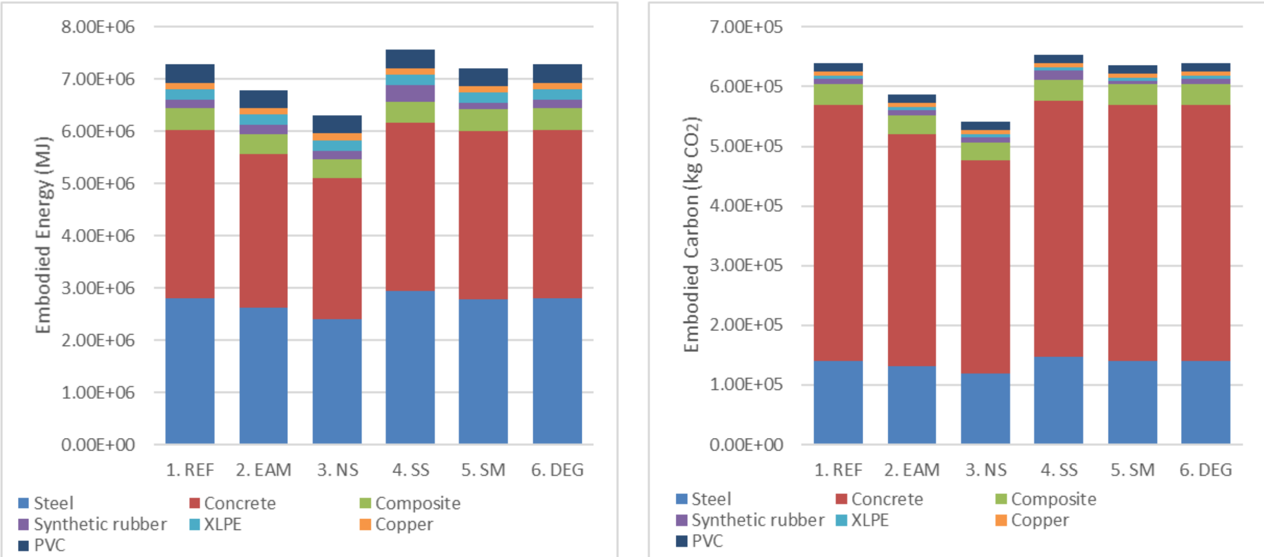

FIGURE 12: EMBODIED ENERGY AND CARBON FOR ALL BREAKTHROUGH VARIANTS, AT THE LEIXOES SITE. CATEGORISED BY MATERIAL

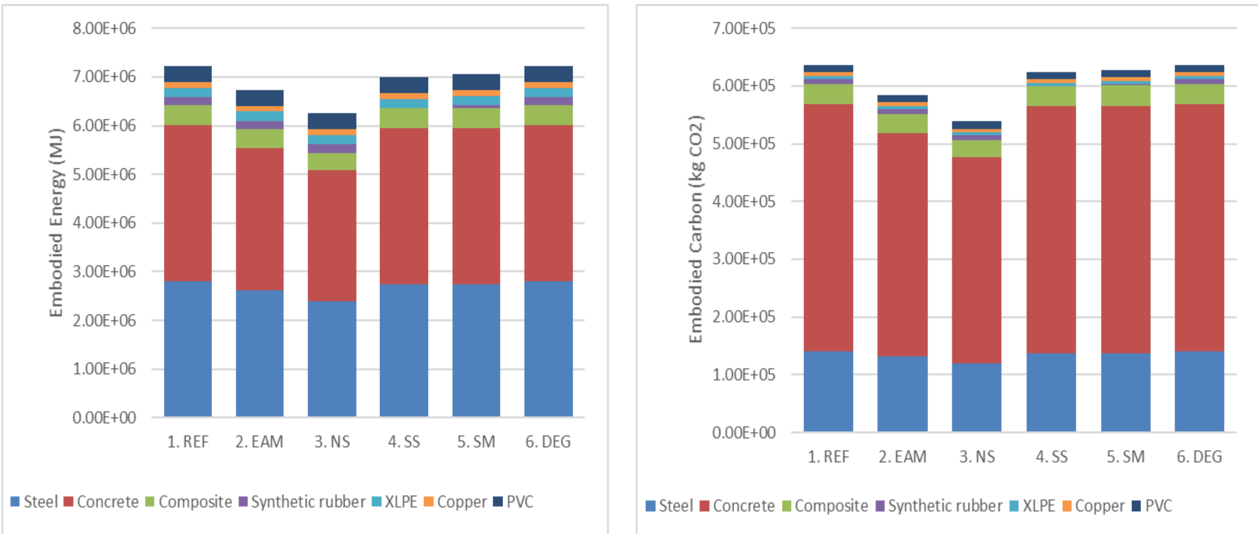

FIGURE 13: EMBODIED ENERGY AND CARBON FOR ALL BREAKTHROUGH VARIANTS, AT THE EMEC SITE. CATEGORISED BY MATERIAL

3.1.2.2. Life-Cycle Stages

The embodied energy and carbon values split up by project stage are presented in Figure 14 and Figure 15 for Leixoes and EMEC respectively, for all 7 breakthroughs. Due to significant reduction in energy and carbon associated with materials (see Figure 12 and Figure 13), the negative spring breakthrough displays the lowest embodied values when summing over life-cycle stages. Savings made by other breakthroughs e.g. in installation phase due to shared moorings (SM), are found not to be as significant as those obtained through savings in material quantities. Results between the EMEC site and Leixoes are comparable, with the expected increase in installation and O&M associated with the Leixoes site, due to larger distance to port and significant increase in water depth.

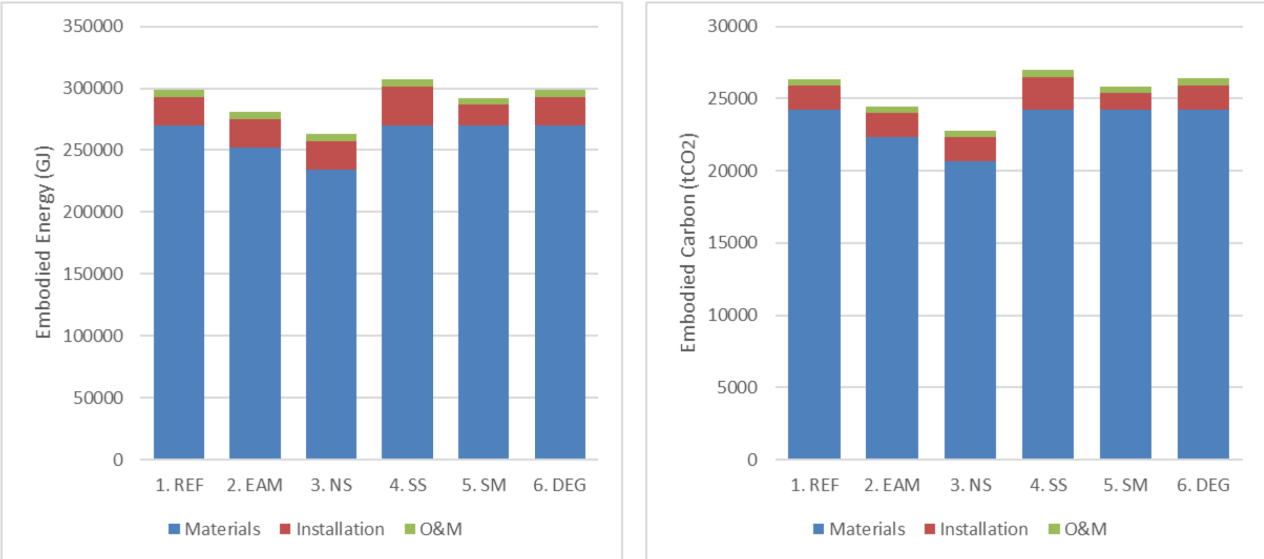

FIGURE 14: EMBODIED ENERGY AND CARBON FOR ALL BREAKTHROUGH VARIANTS, AT THE LEIXOES SITE. CATEGORISED BY LIFE-CYCLE STAGE. O&M IS SHOWN AS PER ANNUM VALUES.

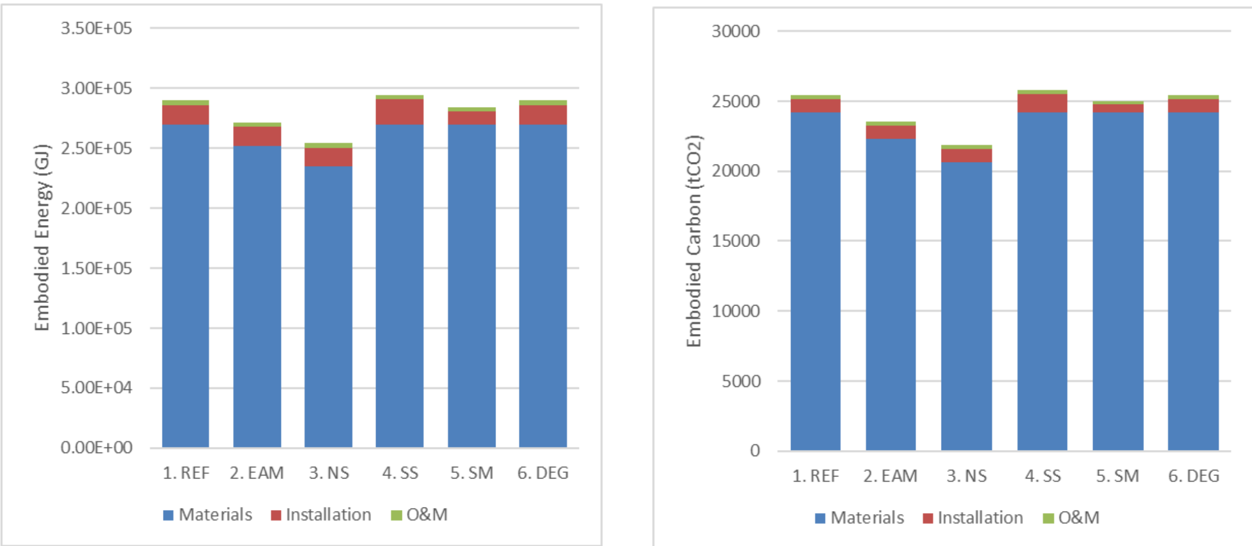

FIGURE 15: EMBODIED ENERGY AND CARBON FOR ALL BREAKTHROUGH VARIANTS, AT THE EMEC SITE. CATEGORISED BY LIFE-CYCLE STAGE. O&M IS SHOWN AS PER ANNUM VALUES.

3.1.2.3. Carbon Intensities

Carbon intensities for each of the breakthroughs, assessed at EMEC and Leixoes, are presented in Figure 16. As expected from previous results, the lowest carbon intensities are observed at the EMEC site with the negative spring design breakthrough implemented. Referring to the carbon intensities of other energy sources (Figure 9) it is evident that all variants explored are still associated with much larger carbon intensities than those of more established renewable technologies. This suggests that the breakthroughs are not significant enough to give the same level of 'carbon efficiency' of these technologies at present.

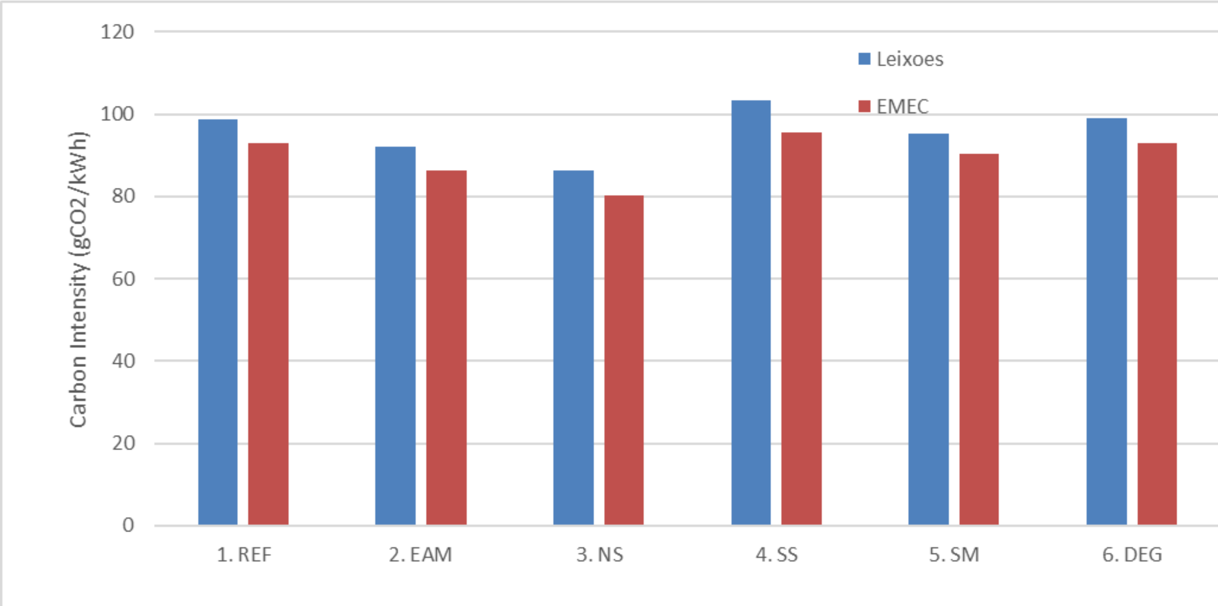

FIGURE 16: CARBON INTENSITIES FOR THE BREAKTHROUGH VARIANTS, ASSESS FOR BOTH LEIXOES AND EMEC SITES

3.1.2.4. Energy and Carbon Payback

The breakeven year for energy and carbon flows for breakthroughs deployed at the Leixoes and EMEC sire can be found in Figure 17. It is evident from these figures that all breakthroughs are relatively comparable, other than the DEG design case. This is a result of the DEG device variant producing significantly less power, which is due to the device being optimised higher T_E sea states than are typical at either site. If this device design is optimised for these two locations the expected energy production will be significantly larger, and hence the breakeven year for energy and carbon will be significantly lower.

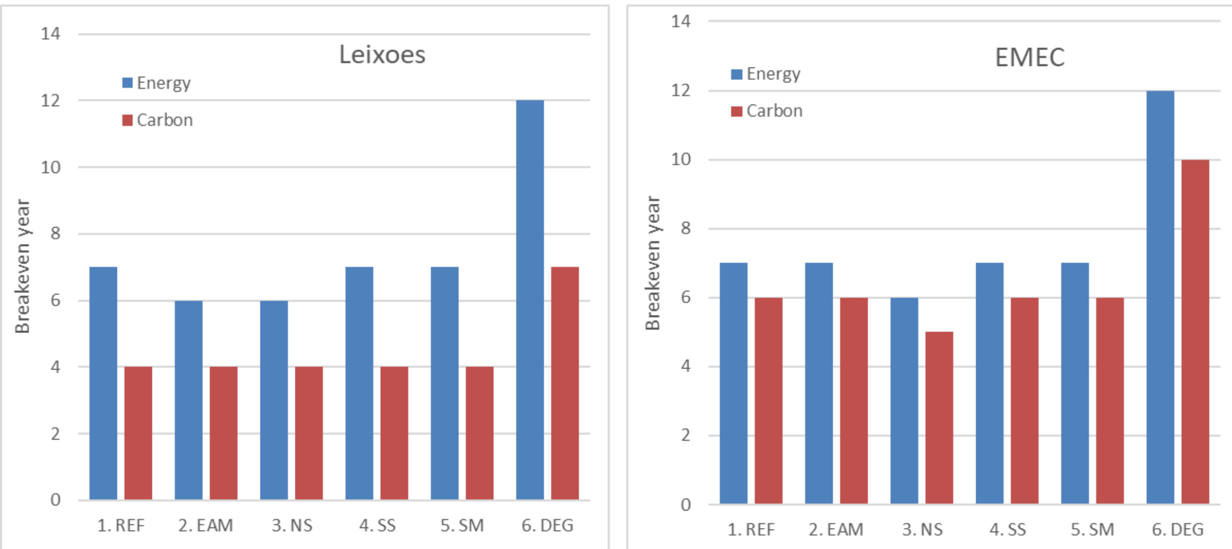

FIGURE 17: BREAKEVEN YEAR FOR CARBON AND ENERGY FLOWS, ASSESSED FOR THE EMEC AND LEIXOES SITES

3.2. Effect of Wave Farms on Economy and Employment in Scotland

Due to the highly location dependent nature of macro-economic studies the IO results are presented in a different form to the LCA, with Scotland and Portugal focused on separately. This section focuses on the result of the farm of OWC devices on the Scottish economy, with baseline results presented in Section 3.2.1, and the influence of breakthrough assessed in Section 3.2.2.

3.2.1. Baseline Results

3.2.1.1. Direct and Type II outputs

The direct outputs for each of the 29 aggregated sectors, for each project stage, are presented in Figure 18. These values are shown per annum of the project stage in question, and as such to obtain total values it is required to consider the number of years of each project phase, detailed in Section 2.4.4. As these represent the direct outputs these are essentially the industries that are being directly 'shocked' by the development of the baseline OWC wave farm in Scotland. As expected, manufacturing sectors are most directly influenced at the manufacturing stage, whilst water transport dominates the expenditure for installation and decommissioning.

The type II outputs shown in the same form as Figure 18 are presented in Figure 19. As these include the direct, indirect and induced effects of the project spend all aggregated sectors have some associated output, and an increase is observed in those sectors directly shocked due to interdependency based multiplier effects. It is interesting to note how certain industry sectors which are not directly shocked have large expected output associated with the project when considering these type II effects. The aggregated sector "Communications, Finance and Business" is the largest of these, however significant output is also associated with the "Education, public and other services" as well as "Wholesale and retail" sectors. This clearly demonstrates the significant and wide-reaching indirect effects resulting from project developments of this type.

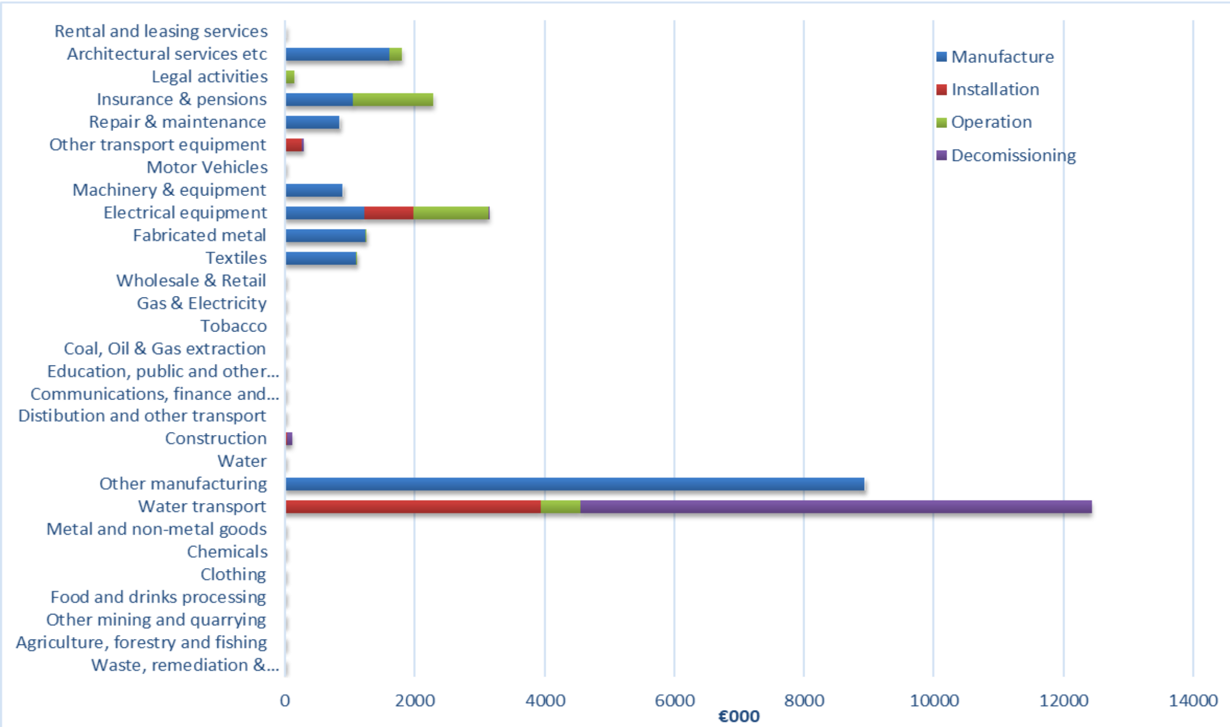

FIGURE 18: DIRECT OUTPUT PER INDUSTRY STAGE PER ANNUM. RESULTS ARE PRESENTED FOR EACH OF THE 29 AGGREGATED SECTORS

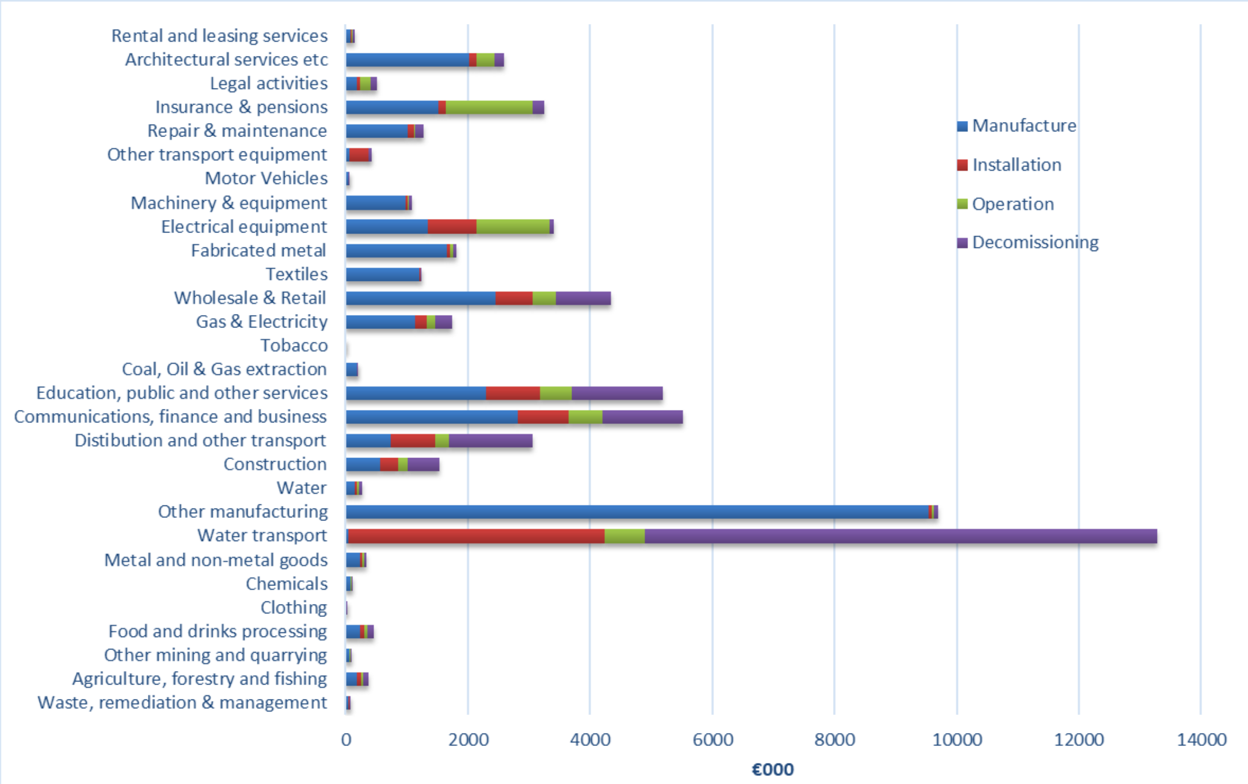

FIGURE 19: TYPE II OUTPUT PER INDUSTRY STAGE PER ANNUM. RESULTS ARE PRESENTED FOR EACH OF THE 29 AGGREGATED SECTORS

3.2.1.2. Type II employment

The type II employment effects, detailed in Table 5, are used to calculate the total type II jobs attributed to each of the sectors associated with direct demand. This includes indirect and induced jobs supported in interlinked sectors resulting from the project expenditure. Summing these and assessing over the project lifecycle yields the graph presented in Figure 20, which represents the resulting jobs across all Scottish sectors in that year of operation.

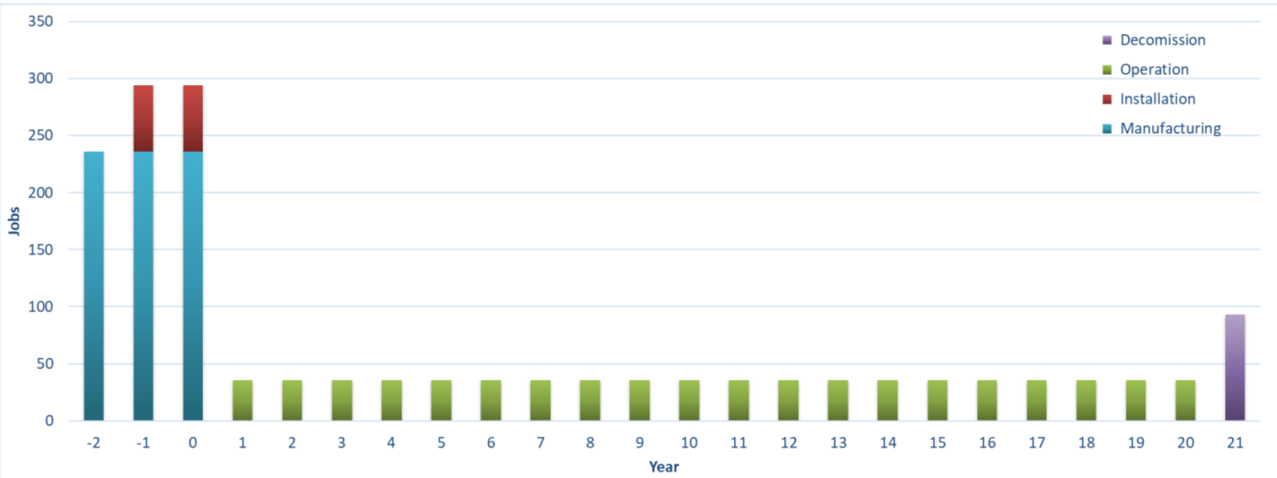

FIGURE 20: TYPE II JOBS AS A FUNCTION OF PROJECT YEAR

During the joint manufacturing and installation phase there is a peak of 293 jobs indirectly supported by the project, whilst in the operational phase this drops to 36. As the nature of the work is consistent

during this operational phase it is inferred that this would represent 36 stable jobs spread out over the Scottish economy. Assessing Figure 18 and Figure 19 it is evident that direct jobs are in insurance, electrical equipment and water transport, with indirect jobs appearing in several other sectors.

3.2.1.3. Type II GVA

The GVA equivalent of Figure 20 is presented in Figure 21, using the GVA effects calculated for the aggregated Scotland sectors (Table 5). Due to jobs and GVA both being heavily correlated to total expenditure an analogous trend with project stage is observed. Peak GVA of £19.2m occurs during the joint installation and manufacturing phase, which reduced to £2.7m in the operations phase.

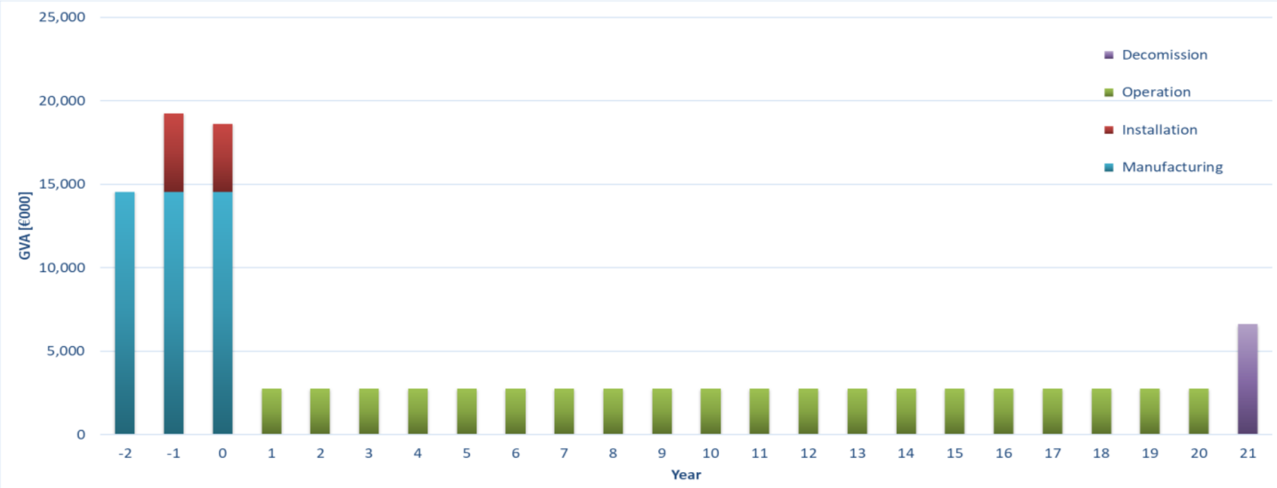

FIGURE 21: TYPE II GVA AS A FUNCTION OF PROJECT YEAR

3.2.2. Influence of Breakthroughs

The influence of breakthroughs on the sectoral outputs, jobs and GVA are assessed in this section, for the proposed wave farm variants deployed in EMEC, Scotland.

3.2.2.1. Direct and Type II outputs

The direct outputs for the 29 aggregated sectors, for each of the breakthroughs, assessed over the different project stages is presented in Figure 22. As expected from the LCA outputs (3.1), the negative spring breakthrough has the smallest quantity of materials and hence lower associated cost, energy and carbon. This causes a reduction in direct sector output as less is being spent in this project phase. This highlights an interesting point, in that, what is essentially good for the project in terms of cost and carbon reduction appears negative in terms of macro-economics. Assessing macro-economic effects from the IO model, it seems favourable to have projects which are just about commercially viable and can sustain themselves over the lifetime, yet are not over-optimised as this results in reduced net spend and associated jobs and GVA. This misses out one part of the equation as it does not what happens to any profits made (assessed through techno-economics) as these will in turn, also influence the macro-economic effects associated with the proposed projects.

Assessing Figure 22 in isolation it is evident that survivability submergence (4) breakthrough offers the largest macro-economic benefit in terms of direct sector output. This is also the case when assessing the type II sector outputs presented in Figure 23. Like the reference case, type II outputs relative to direct outputs show a significant increase for all breakthroughs, and a wide range of other sectors are stimulated either indirectly or through induced effects.

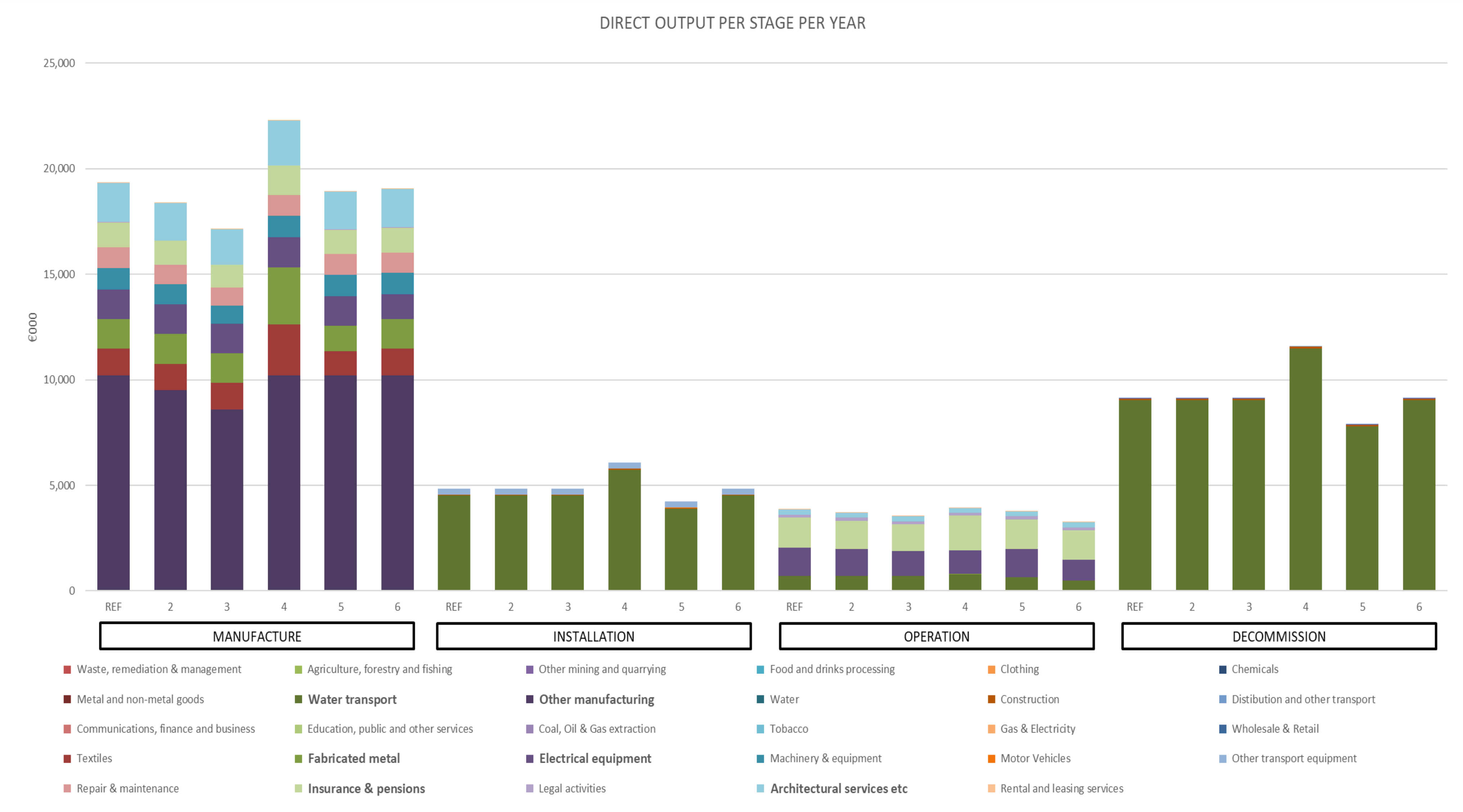

FIGURE 22: DIRECT OUTPUT PER STAGE PER YEAR FOR EACH OF THE BREAKTHROUGHS. RESULTS ARE SHOWN SEPARATED INTO THE 29 AGGREGATED SECTORS

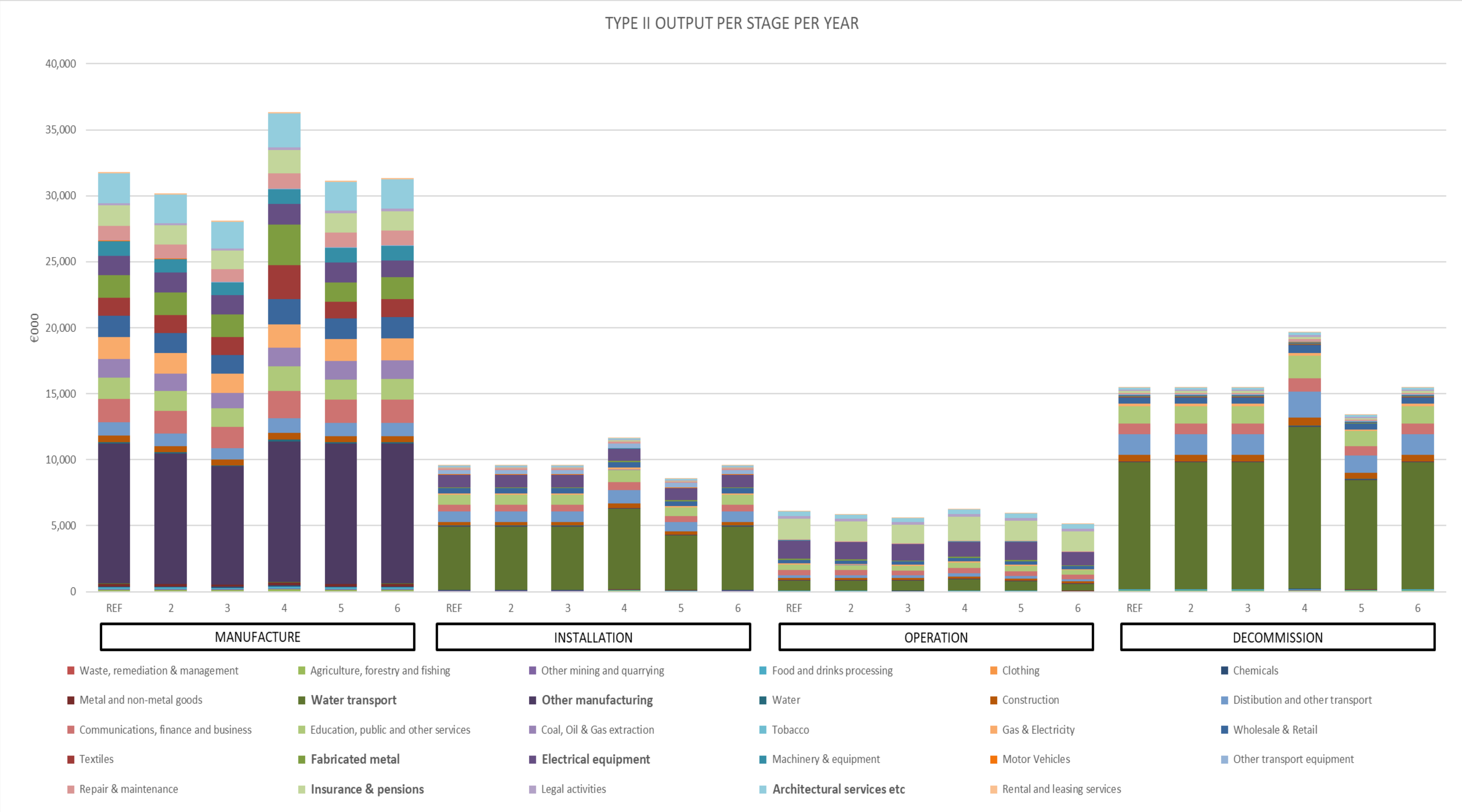

FIGURE 23: TYPE II OUTPUT PER STAGE PER YEAR FOR EACH OF THE BREAKTHROUGHS. RESULTS ARE SHOWN SEPARATED INTO THE 29 AGGREGATED SECTORS

3.2.2.2. Employment

The employment associated with each of the breakthroughs, for each of the main project stages is presented in Figure 24. As with the reference case these employment figures mirror the type II outputs associated with the project variants. Due to the survivability submergence variant costing more in terms of manufacture and installation, this breakthrough supports the highest number of jobs throughout the Scottish economy. This is the case for all of the project phases. As expected from direct and type II output values, the negative spring variant is associated with the least number of jobs.

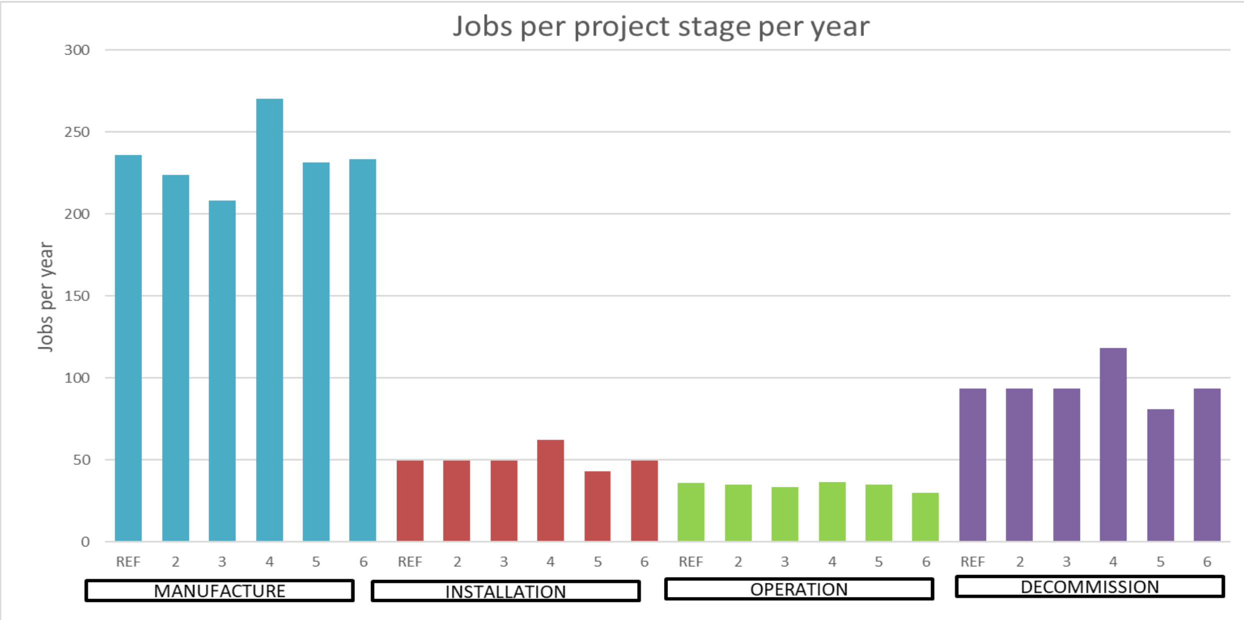

FIGURE 24: JOBS ASSOCIATED WITH EACH OF THE BREAKTHROUGHS FOR EACH OF THE PROJECT STAGES

3.2.2.3. GVA

GVA values associated with the breakthroughs are presented in Figure 25, and show the same trend as the type II employment resulting from the proposed WEC farms.

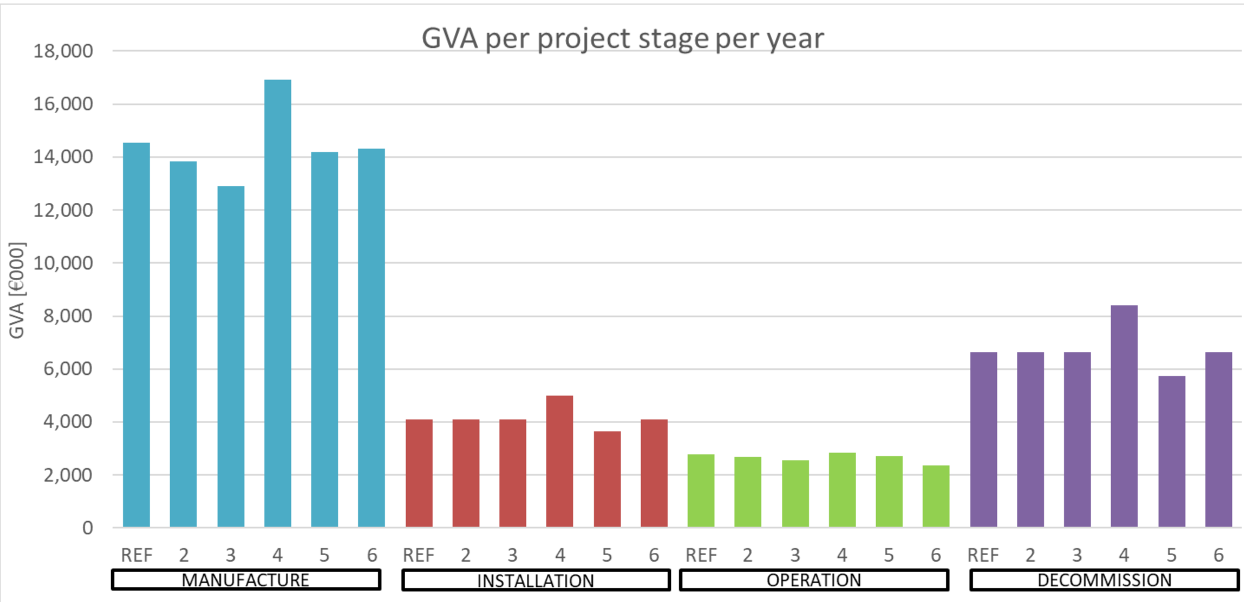

FIGURE 25: GVA ASSOCIATED WITH EACH OF THE BREAKTHROUGHS FOR EACH OF THE PROJECT STAGES

3.3. Effect of Wave Farms on Economy and Employment in Portugal

Baseline IO modelling results for the farm of OWC devices deployed in Portugal are presented in Section 3.3.1, with the influence of breakthrough assessed in 3.3.2.

3.3.1. Baseline Results

3.3.1.1. Direct and Type 2 outputs

Direct outputs (demand) for the 29 aggregated sectors are presented in Figure 26, shown as per annum values for each of the 4 project stages. Comparing with the Scotland equivalent, Figure 18, it is evident that there is a significant increase in the per annum spend associated with water transport, fabricated metal and electrical equipment. This is a combined result of an increased distance from port and water depth. Electrical cabling and associated metal is a function of both of these factors, whilst the increased water transport is only affected by the distance to suitable port infrastructure. The remaining expenditure remains equivalent to Scotland for all aggregated sectors.

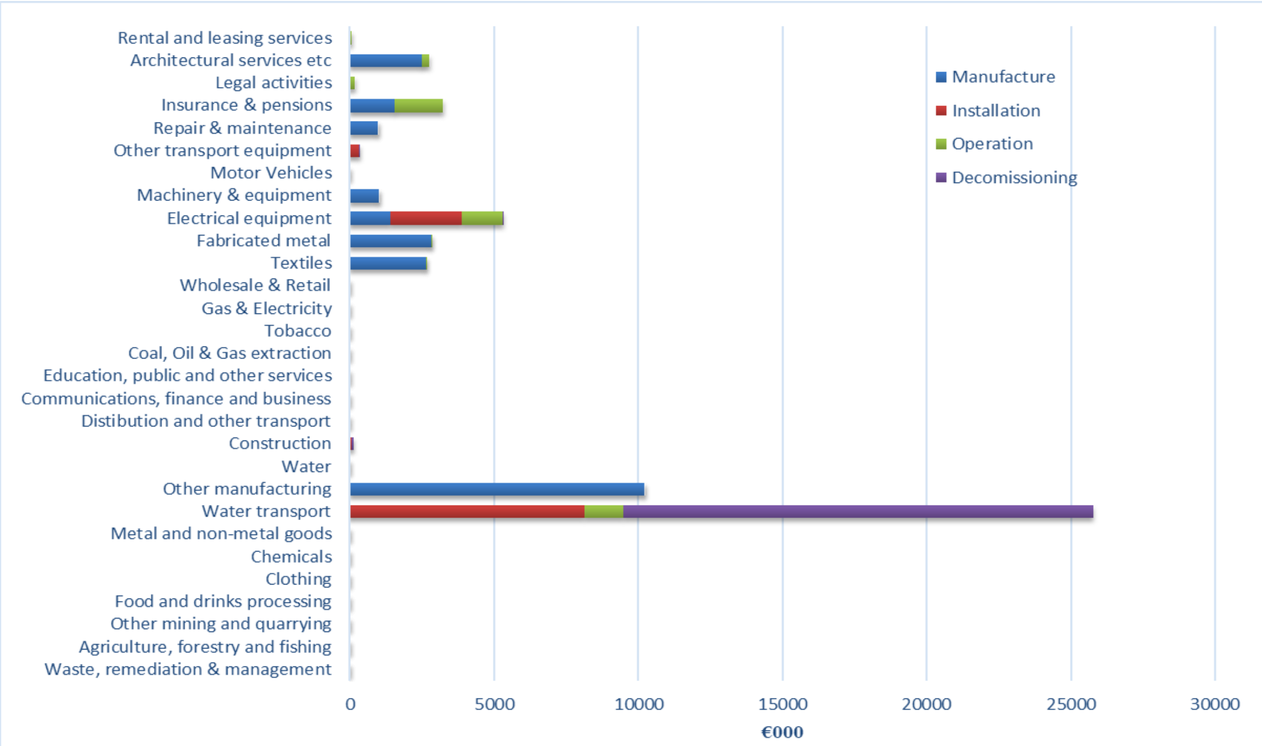

FIGURE 26: DIRECT OUTPUT PER INDUSTRY STAGE PER ANNUM. RESULTS ARE PRESENTED FOR EACH OF THE 29 AGGREGATED SECTORS

The type II outputs corresponding to the direct sectoral spend presented in Figure 26 is shown in Figure 27. The same relative increases associated with greater port distance are visible when comparing with the Scotland equivalent. It is evident that a wide range of Portuguese economic sectors benefit from the proposed wave farm throughout each of the four project phases. Differences in the magnitude of non-directly shocked sectors are noted due to location-specific interdependencies of economic sectors.

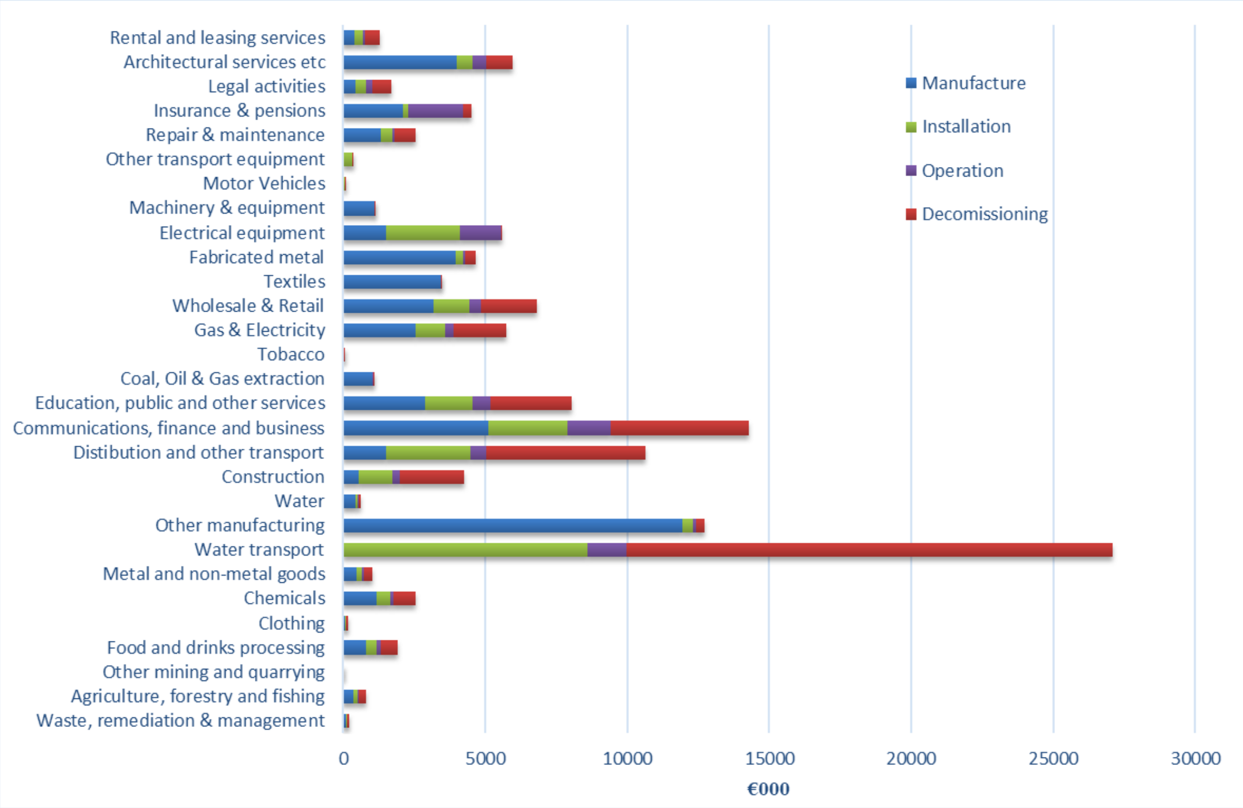

FIGURE 27: TYPE II OUTPUT PER INDUSTRY STAGE PER ANNUM. RESULTS ARE PRESENTED FOR EACH OF THE 29 AGGREGATED SECTORS

3.3.1.2. Type II employment

Type II employment effects for Portugal have been calculated using the number of employees associated with each of the aggregated sectors relative to the total output, along with the type II Leontief matrix (see 2.4.5.2). Computing the type II jobs created for each year results in the graph presented in Figure 28. As expected, the jobs required (plus those supported indirectly through this requirement) are large for the installation and decommissioning phase due to the significant effort in installing and removing the devices at the Leixoes location. A peak of 737 jobs are supported for two years during the joint installation and manufacturing phase.

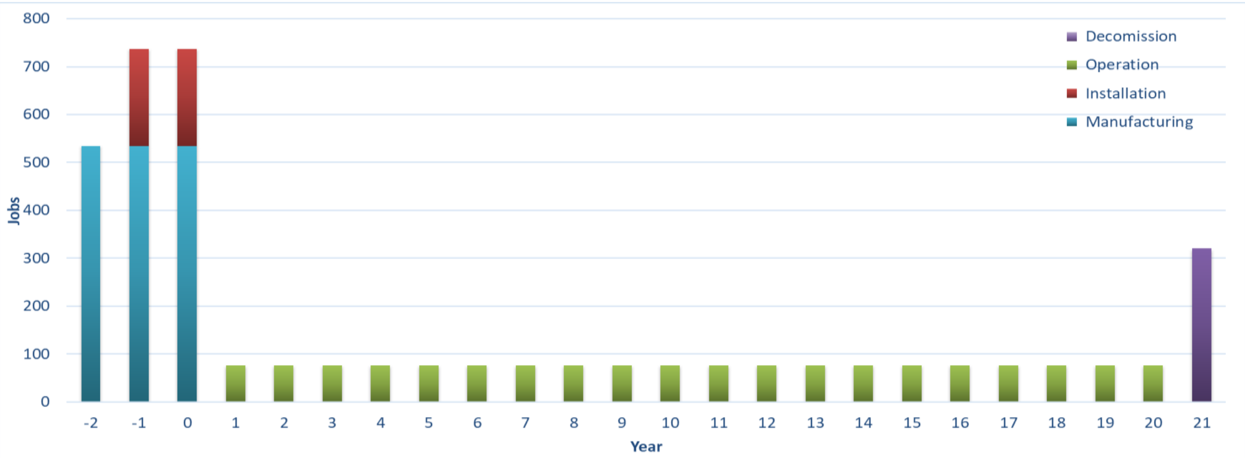

FIGURE 28: TYPE II JOBS AS A FUNCTION OF PROJECT YEAR

3.3.1.3. Type II GVA

As expected, the GVA as s function of project year is similar to that of the associated employment. In comparison to Scotland, the total GVA for all sectors in slightly higher, reflecting the total project costs being larger when deployed at the Leixoes site.

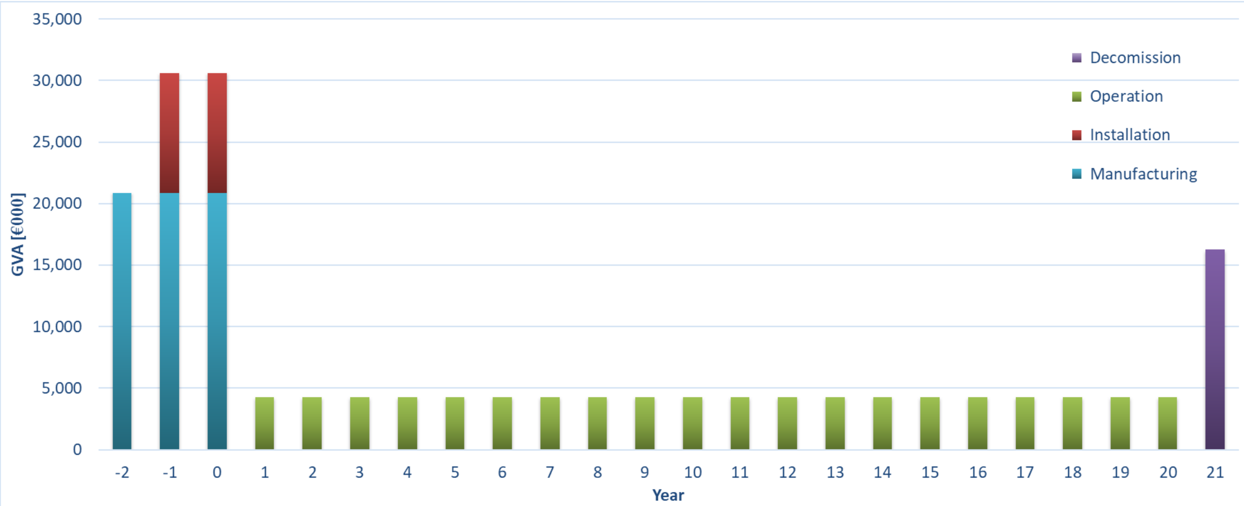

FIGURE 29: TYPE II GVA AS A FUNCTION OF PROJECT YEAR

3.3.2. Influence of Breakthroughs

The influence of breakthroughs on the direct outputs of Portuguese economic sectors are explored in this section along with the type II outputs, jobs and GVA.

3.3.2.1. Direct and Type II outputs

The direct and type II outputs are presented in Figure 30 and Figure 31 for each of the 29 aggregated sectors and each of the project stages, for every assessed breakthrough. Values are presented per year of each phase. It is evident that the negative spring breakthrough (3) is associated with the least expenditure on materials, with shared moorings (5) the least for installation and decommissioning. In terms of macro-economic effects, this causes a reduced output (direct & type II), with the least cost-effective (4: survivability submergence) seemingly the most beneficial to the Portuguese economy for all of the project stages.

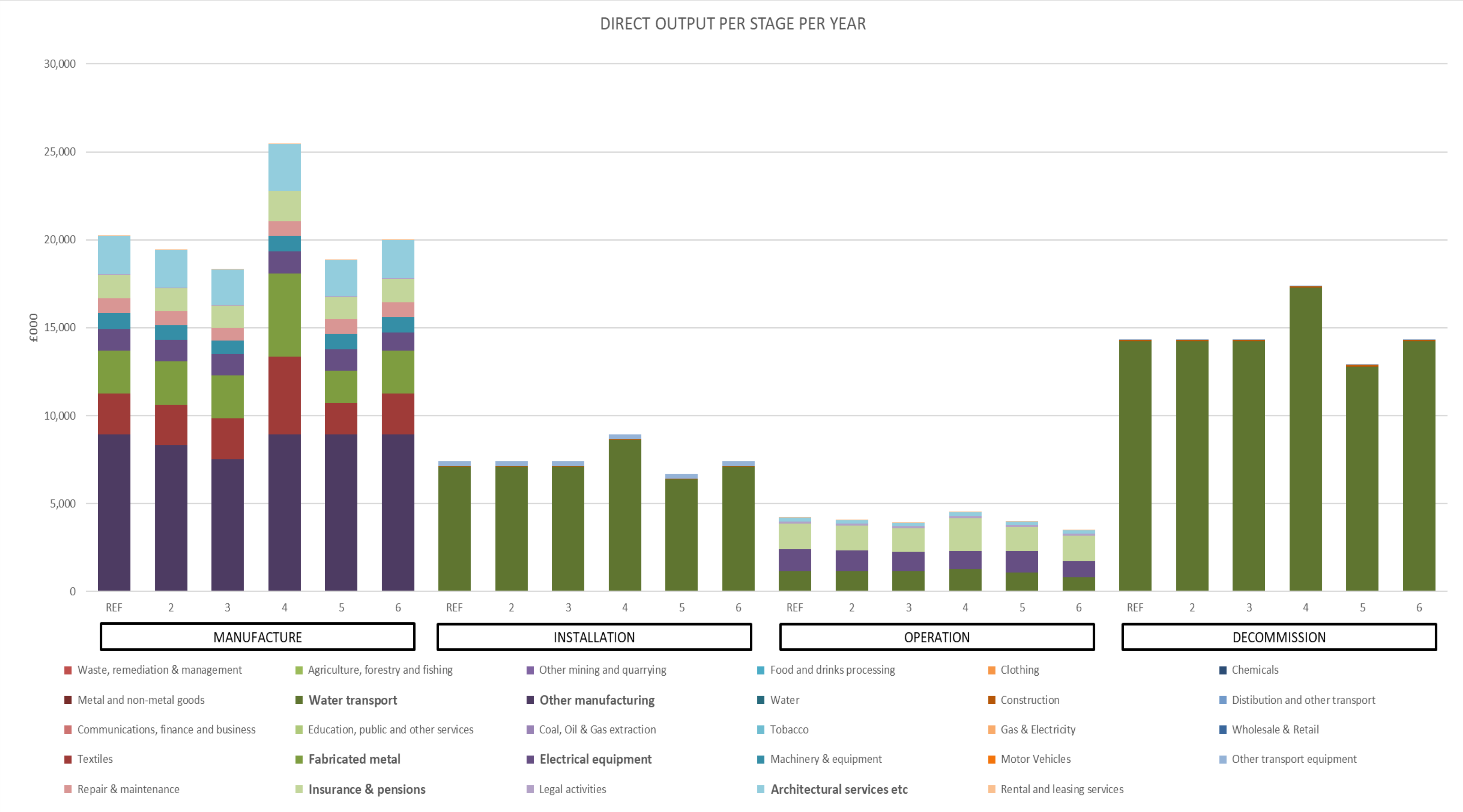

Figure 30: Direct output per stage per year for each of the breakthroughs. Results are shown separated into the 29 aggregated sectors

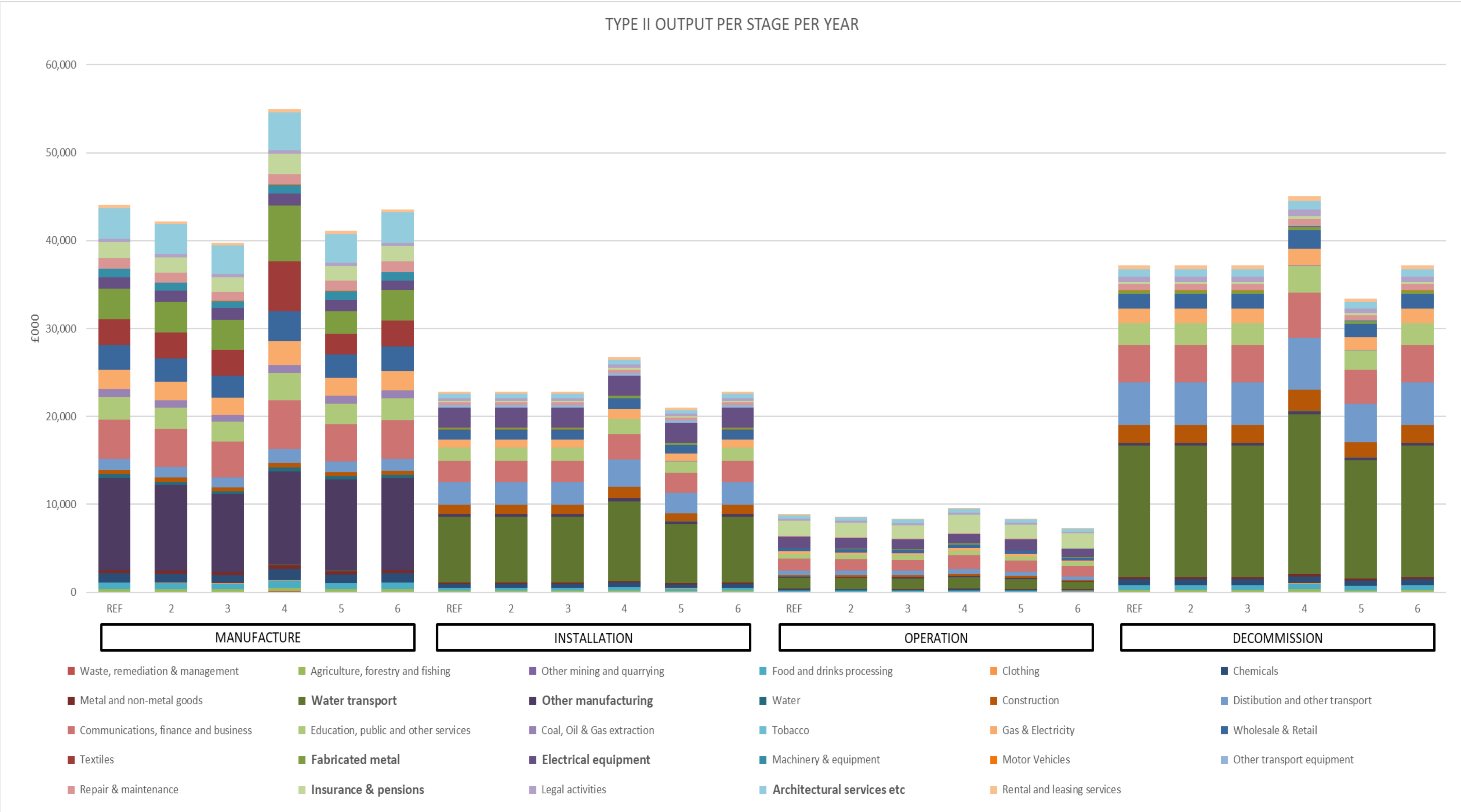

FIGURE 31: TYPE II OUTPUT PER STAGE PER YEAR FOR EACH OF THE BREAKTHROUGHS. RESULTS ARE SHOWN SEPARATED INTO THE 29 AGGREGATED SECTORS

3.3.2.2. Employment

The number of jobs per year, for each of the project phases, and for every breakthrough is presented in Figure 32. Like the Scotland case, the employment figures follow the same trend as the total type II output for the breakthroughs, with breakthrough 4 being associated with the largest number of jobs. The survivability submergence breakthrough, in theory, supports and requires the largest number of jobs for all project phases.

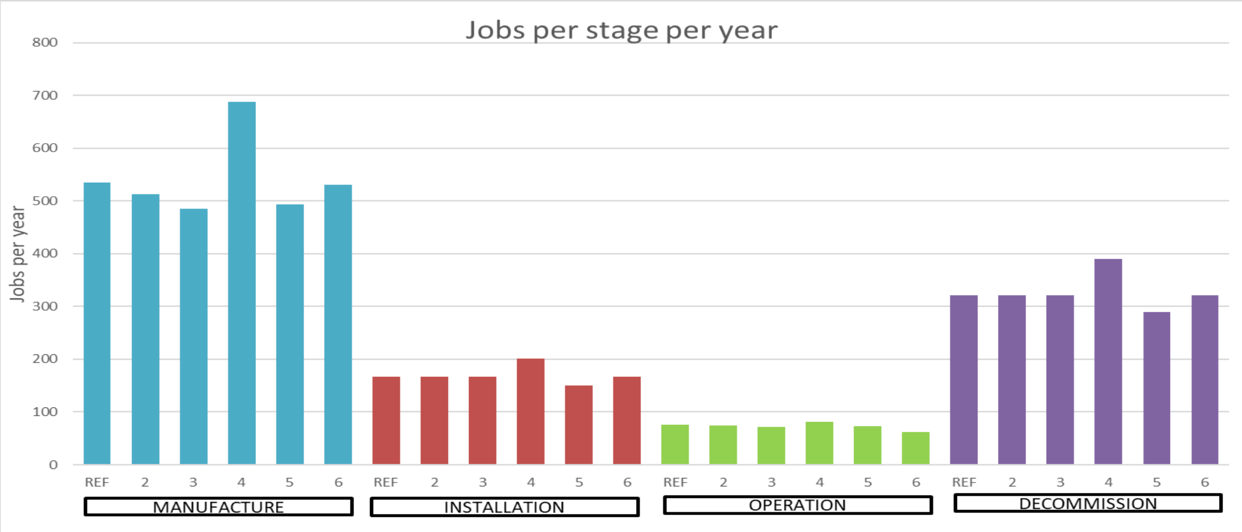

FIGURE 32: JOBS ASSOCIATED WITH EACH OF THE BREAKTHROUGHS FOR EACH OF THE PROJECT STAGES

3.3.2.3. GVA

The type II GVA (like employment) follow the total type II outputs, with the manufacturing phase associated with the largest peak GVA per annum. The operation phase, which spans 20 years, contributes the most to total GVA over the project lifetime. In general, the GVA, like most other macro-economic outputs for this project, are higher for the Portugal case study than the Scottish equivalent. This is due to the larger distance to port and deeper water meaning there is extra spend for manufacturing of electrical and mooring cables and the installation thereof.

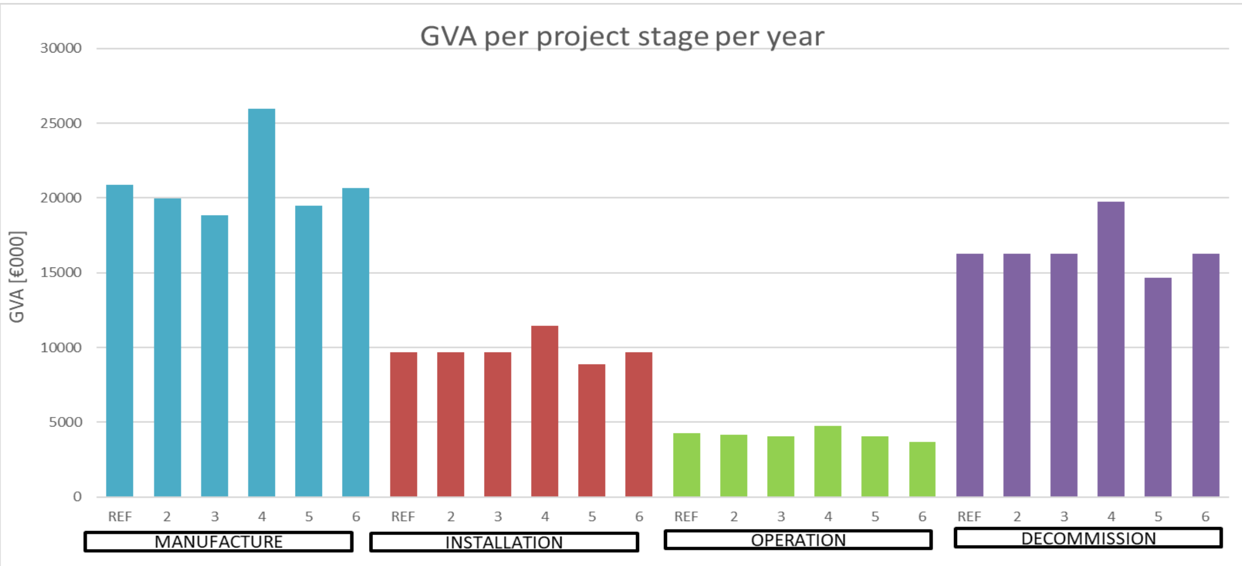

FIGURE 33: GVA ASSOCIATED WITH EACH OF THE BREAKTHROUGHS FOR EACH OF THE PROJECT STAGES

4. Social Impacts and Acceptance

As offshore renewable energy generation schemes become increasingly prevalent throughout Europe and the UK alike, social acceptance of such projects play an important role in their future development and expansion. It is therefore necessary to develop a thorough understanding of the effects a given project might have on the society and how it might respond to it. Hence, this section aims to explore the likely social impacts and acceptance of the proposed OWC wave farm, and variants thereof, using a combination of relevant literature and profiles of the locations themselves. A brief overview of likely social impacts is described in Section 4.1, prior to discussing the relevance of the 'NIMBYism' concept in Section 4.2 Section 4.3 assesses two case studies in combination with the EMEC and Leixoes site to assess the likely outlook and acceptance in these two regions. Speculation on the additional influence of breakthrough type is offered in 4.4.

4.1. Overview of Social Impacts

When considering any industrial development, it is necessary to consider direct and indirect effects induced by the prospective project. Plentiful literature exists on the potential impacts of marine developments on local society. [16] is one such study, which assesses the social impacts of tidal barrages whilst providing a useful overview of the types of effects that may arise from such developments. Key impacts highlighted in this, and other studies are detailed below:

Negative:

Direct:

- Noise generated during material transportation, construction, and operation.
- Limiting navigation of commercial, recreational, and military vessels.
- Changes and obstructions to the seascape.
- Possible damage to beaches, shallow and deep-water ecology, and a decrease in water quality, especially during construction.
- Possible damage to key pieces of archaeological and geographical heritage.

Indirect:

- An increase in flood risks as a result of salt marsh erosion and other environmental impacts of installation.
- A decrease in tourism as a result of environmental changes.
- Risks to commercial and recreational fishing as a result of changes in local fish populations.
- Long term disruptions in local ecology.

Positive:

Direct:

- Benefits to local infrastructure through building new roads and upgrading existing ones for material transport.
- "An increase in bathing quality … as a result of reduced currents" [16] upstream the barrage.
- Increased employment associated with the project.

Indirect:

- The devices themselves "can become tourist attractions," as in the case of The Thames Barrier, the La Rance tidal barrage, or the SeaGen device installed in Strangford Lough [19].

The extent of these effects relies on a number of sentimental, environmental, and geographical factors. Some of the less obvious impacts are expanded on in the following sections.

4.2. NIMBYism

Social acceptance depends on the comparison of the positive and negative impacts outlined above on the everyday lives of the local residents. Generally speaking, temporary effects such as the noise generated during construction and decommissioning play a lesser role than the long-term effects associated with operation and maintenance. The long-term effects, such as noise generated during operation depend largely on the proximity of the devices to the shoreline, their size and visual obstruction. [17] concludes that the public attitude towards such developments is characterized by a general support, yet frequent local opposition. This trend is often referred to as NIMBYism (Not In My BackYard). However, it is consistently argued that the term is outdated and fails to capture the many factors that shape public opinion [18]. Additionally, the term implies egocentrism and ignorance, thus discrediting well founded opposition. Contemporary literature therefore tries to avoid the term [19]. Despite the term falling out of favor, the consequences of NIMBYism are important to understand and consider in any development. It is therefore expected that people who state that they support a project will actually oppose it if it is decided to be constructed near to their homes or businesses.

4.3. Case Studies

To make a reasonable projection of the societal effects of the devices proposed in the WETFEET project, two case studies are used. These studies assess the installation of equivalent devices in areas socio-economically similar to EMEC and Leixoes,. Additional site-specific information is used to draw further inferences on likely social effects and responses. These two case studies are summarized below:

Case Study 1 is based on the investigation of societal acceptance of the construction of a marine current turbine in the context of small rural communities of Strangford and Portaferry, Northern Ireland [19]. The study employs a multi method survey of some 313 residents of the two towns, and due to socio-economic similarity is particularly relevant to the development on Orkney discussed in this report.

Case Study 2 [16] explores the effects of the historic La Rance tidal barrage in northern France on the local marine ecosystem. Since possible damage to the environment is often one of the key influences on public opinion [17] [19], the study helps enhance understanding of such potential environmental impacts, and develop means of mitigation. Also, La Rance has become a tourist destination, which is a good example of an indirect positive effect on the local community a renewable energy scheme can have.

The following table outlines the key demographics and information between the locations discussed in the case studies and the ones under consideration in this deliverable. While the average income is similar between all cases, the differences in population and the presence of previous developments may result in slight different trends in social acceptance. These are discussed further in Sections 4.3.2 and 4.3.3.

TABLE 6: SUMMARY OF CASE STUDY LOCATIONS IN COMPARISON TO THE EMEC AND LEIXOES SITES

	Case Study 1 [19]		Case Study 2 [16]		Orkney	Leixoes
Town	Strangford	Portaferry	La Richardais	La Briantais	Stromness	Matosinhos
Proximity to the Shore (km)	< 1	3	< 1	< 1	2	30
Population	474 [20]	2514 [20]	2367	35400	2200 [20]	175000
Average Income €/ household member / year	18177 [21]	18177 [21]	24884	24884	21238 [21]	11848
Previous Developments	Yes	Yes	No	No	Yes	No

4.3.1. Implications on Societal Acceptance

Case study 1 [19] concludes that place attachment and sentimental value play an important role in shaping public opinion, however, such factors are difficult to quantify. It is more practical to rely on qualitative studies of behavioral patterns in social acceptance. It is demonstrated that residents which support renewable energy installations interpret them as a means to "enhance the distinctiveness of the area" [19]. The study also concludes that another reason for support is the idea that such installments visually "fit the character" of the region and the people who reside there. One can infer that the aforesaid character is one of progressivism and care for the environment, since the majority of the supporters also expressed a belief that the project would help combat climate on a global scale. Building on this, it is reasonable to argue that places with a history of social acceptance of renewable energy in the past are a lot more likely to accept similar developments in the future than those without.

According to [22], a significant case against offshore renewables is the potential damage to the local marine ecosystem, which would in turn influence the lives of commercial and recreational fishermen [17]. [23] specifically explores the attitudes of Scottish fishermen towards offshore renewable energy. The study determines that the majority of fishermen surveyed (81%) have either a positive or a neutral attitude towards new offshore installations unless it directly impacts their practice, suggesting that to mitigate the risk of social opposition, the devices must be implemented such that they have a minimal effect on the local fisheries. This can be done at the project planning stage. Abundant literature exists on the impacts of total power devices on fish mortality, migration patterns, and reproductive behavior and potential means of mitigation [24][25][16]. Additionally, multiple species of fish have demonstrated an ability to adapt and circumvent obstacles introduced to their natural habitat [26]. Given the residents' perception of the device as environmentally friendly and progressive, it is important to clarify the mitigation strategies used to minimize the potential damage to the local marine ecosystems.

Case study 2 shows that despite considerable disruption to the water flow, the La Rance barrage did not have a long term negative effect on the local marine environment. However, it did take nearly a decade for full restoration. Damage to the environment is frequently cited as a considerable obstacle to societal acceptance [22]. Based on this, the study then outlines various means of mitigation that can be implemented during the project planning stage. Furthermore, since La Rance has become a local tourist attraction, it verifies the conclusions drawn by the first study in that renewable energy installment have an ability to add to the "distinctiveness" and character of the area, which positively influences social acceptance.

4.3.2. Orkney

In its vision for the economic and social future of the islands, the Orkney government states that the key goal is creating a "healthy environment supported by thriving economy" [27]. Renewable energy developments play an integral role in achieving this vision, giving the immense wave (tidal and wind) potential of the islands [28]. Numerous sustainable energy schemes have already undergone an extensive planning stage, and the residents have been aware of such developments for years [28].

Based on the conclusions drawn in 4.3.1, it can thus be inferred that the overall perception of projects like the ones proposed in this paper is positive; the residents have adopted a progressive, environmentally conscious attitude, and further developments will thus further enhance the "character" of the area, as discussed in the previous section. Taking the above into consideration, a strong case can be made for minimal social opposition.

4.3.3. Leixões

Unlike the nearby towns in Orkney, Leixoes is a suburb of the greater Porto area. Living in much more metropolitan setting, the local residents are exposed to greater levels of noise. Also, the device itself is considerably further from the shore, which reduces both noise during operation and the obstruction of seascape. However, since it is a commercial port, it is likely that larger scale opposition from the fishing and transportation industries will arise.

4.4. Influence of OWC Breakthroughs

It is expected that the influence of the breakthroughs on social impact and acceptance will generally be low, with opinion determined largely by the location and general nature of the development as a whole. However, small differences in social acceptance may arise if people are properly informed over the nature of the devices, which will be altered by the breakthroughs present in the device. The potential influence of these are detailed below:

2. **Enhanced Added Mass**
   Should result in increased power output which may influence perception of the effectiveness of the project and its overall positive influence.
3. **Negative spring**
   Similar to EAM. Increased power output, if communicated effectively, may slightly influence public perception. In addition, these devices are smaller and as such have less visual impact. Being easier to handle may result in smaller vessels being required, which will further influence the expected visual impact.
4. **Survivability submergence**
   If this survivability strategy makes a large difference in visible failures, or indeed catastrophic failures and beaching of devices, this may prevent a negative public perception being developed.
5. **Shared moorings**

Shared moorings will reduce the footprint on the seabed of the devices, and will be more environmentally friendly. If this is well communicated to the public this should positively impact the social acceptance of the project.

6. **Dielectric elastomer generator**

   This breakthrough should result in reduced noise from the devices in operation, which, dependent on the distance to population may have a positive impact on the perception of the WEC farm.

5. Additional Discussion

5.1. Potential for Integrated Analysis Approach

In this deliverable, along with the deliverable focusing on the techno-economic modelling (D7.3), the energy & carbon flows, micro and macro-economics, and social impacts of the wave farms and breakthroughs are assessed. In general, however, these have been assessed in isolation. The coupled techno-economic—LCA—IO model developed for this work enables the possibility of a more joined up design and analysis approach, considering these factors in combination.

It was noted when assessing macro-economic effects of the wave farm and breakthrough variants, that breakthroughs which are associated with the largest number of jobs and highest GVA were those that were likely the poorest performers in terms of techno-economics. This highlights that the overall benefit cannot be analysed from macro-economics alone, as it ignores the economic viability of the project in question, and assumes that money will continue to be spent on projects which have low (or negative) profitability. Although not assessed in this deliverable, the techno-economic—IO model would enable a more joined up analysis approach to be carried out to assess the overall benefit from various stakeholder's perspectives: incorporating project success and profitability into overall macro-economic benefit.

Design decisions are driven by technical and techno-economic performance, with energy and carbon flows simply a consequence of these design decisions. It was noted, however, that certain design decisions, despite reducing cost, result in large increased in the embodied energy and carbon. A particular example of this was the use of concrete, typically used to reduce structural cost, yet consequently incurs significant reduction in energy and carbon performance. The ability to assess the wider influence of design decisions enables a more holistic viewpoint to be taken on the value of renewables projects. If these projects are incentivised by government bodies for the purpose of reducing carbon emissions, then the explicit consideration of internal carbon emissions associated renewables projects should clearly be considered to assess the projects with the largest overall benefit.

6. Conclusions

This report assesses the energy and carbon, macro-economics and social acceptance associated with a farm of OWC devices deployed in Leixoes, Portugal, and Orkney, Scotland. In addition, the influence of 6 different technical variants of the wave farms are analysed. Regardless of the breakthrough applied it is found that the energy and carbon performance is much greater than that of fossil fuels, yet lags behind more established renewable technologies due to the large amount of material required per unit of electricity generated. Macro-economic effects are found to be significant and wide reaching; positively benefiting all regional economic sectors, particularly those associated with electrical equipment, manufacturing and water transport. High social acceptance is expected in Orkney due to existing offshore renewable energy developments and attitude towards renewables, whilst in Leixoes some opposition may result from fishing and transport sectors due to proximity to a major port.

The relative benefit of breakthrough on the energy & carbon performance and macro-economics are summarised in Table 7, including the reference case. It is noted that there is not one technical breakthrough that is best for energy & carbon, macro-economics and techno-economics (D7.3). The Negative Spring breakthrough provides the most favourable energy performance and techno-economics, yet due to this high performance it has lower expenditure and hence results in fewer jobs and GVA.

TABLE 7: BREAKTHROUGH RANK IN TERMS OF CARBON INTENSITY AND MACRO-ECONOMIC BENEFIT

	Carbon intensity rank	Employment & GVA rank
1. REF	4	2
2. EAM	2	5
3. NS	1	6
4. SS	6	1
5. SM	3	4
6. DEG	5	3

It is not expected that the influence of breakthrough will have significant effect on social acceptance of the proposed projects, as the existence and nature of the development remains largely unchanged. It is however concluded that, if communicated effectively, all of the breakthroughs have the potential to positively impact social acceptance. In particular the Negative Spring breakthrough may be perceived most favourably due to larger power output, reduced size and visual impact.

In general, the analysis presented in this report highlights, in detail, the significant and wide-reaching benefits of deploying the proposed wave energy farms. The tools developed to carry out this analysis enable assessment of the wider effects of deploying these technologies, and should be a useful tool for the nascent wave energy sector.

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