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Demonstration of a Socio-economic Cost of Energy Analysis of a Wave Energy Converter Array

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***Abstract*—Levelised Cost of Energy (LCOE) is a well established metric for evaluating the economic viability and competitiveness of energy generation technologies. LCOE takes account of the energy generated by a technology and the different expenditures incurred during its manufacture, deployment, operation and decommissioning to yield a cost for a unit of electricity. Numerous studies have presented the LCOE of Wave Energy Converters (WECs), with many highlighting the difficulty of reducing costs to be competitive with alternative energy generation technologies.**

The Socio-economic Cost of Energy (SCOE) method considers how project spend can influence the social environment. SCOE can be used to demonstrate how spend in a project's cost centres can benefit economies through job creation and the generation of economic activity etc.

This paper presents one method of performing an SCOE evaluation of a WEC array. The methodology presented estimates job creation and Gross Value Added (GVA), in a region of interest, that is due to the manufacture, deployment, operation and decommissioning of a WEC array. The methodology is accompanied by a case study that demonstrates the SCOE approach and also presents an application of a reverse LCOE methodology. The reverse LCOE methodology was adopted to provide estimates of the gross spend on multiple WEC cost centres and to demonstrate the approach. The results of the case study demonstrate how the SCOE methodology can be used to sanity check early projections of WEC project cost centre breakdown. The SCOE methodology can also be used as a tool, by both project developers and funding bodies, to plan, and estimate the results of, externally beneficial WEC development pathways.

***Index Terms*— SCOE, Reverse LCOE, Wave Energy Converter, Methodology**

I. INTRODUCTION

Due to the magnitude of the resource and its complimentary phasing relative to wind and solar power, which facilitates the integration of more renewables into the grid, wave power is seen is a promising resource that will have to be utilised if Europe is to achieve its ambitions renewable energy targets [1], [2]. As a leader in the field of wave energy development [3], Europe stands to benefit from the development of the new industry, gaining from job creation and the increase in economic activity due to its development and growth [4], [5]. This opportunity has motivated an extensive research and development effort both by the Commission and Member States in the last decade.

The Socio-economic Cost of Energy ($SCOE$) methodology presented in this paper was developed for inclusion in an overall economic model that has been created for the OPERA (Open Sea Operating Experience to Reduce Wave Energy Cost) project, a European collaborative project funded by the European Commission under the H2020 LCE-02-2015 call [6].

The ultimate aim of OPERA is to gather open-sea operating experience to reduce the cost of wave energy. OPERA's aim is achieved through utilising the opportunity to test on a nationally funded floating Oscillating Water Column (OWC) Wave Energy Converter (WEC) during open-sea trials at the Biscay Marine Energy Platform (*BiMEP*) [7] (an open-sea test facility for research in Spain). This is with a view to obtaining data and experience that will lead to improved survivability and reliability of future WEC projects, reduced technological and business risk and validation of promising cost-reducing technologies.

The OPERA consortium brings together world leaders in their respective work packages to progress the floating OWC's components (mooring system, air turbine and control) from Technology Readiness Levels (TRL) 3-4 to TRL5. The open sea trials of the WEC will progress it from TRL4 to TRL5.

One of tasks within OPERA is to develop an economic model that contains three parallel streams, including: a Levelised Cost of Energy ($LCOE$) calculation, a Life-Cycle Assessment (LCA) calculation and a $SCOE$ calculation. Operational data, gathered from the OPERA project developers and the open-sea trials, will be input into the model to reduce uncertainty, particularly in operating costs. This gathered operational data will enable greater accuracy in the estimation of WEC project costs and environmental and socio-economic impacts. Lessons learnt from the economic model's development with operational data will inform further WEC economic model design.

This paper will proceed as follows. Section II highlights a number of studies that have evaluated technologies on how they influence socio-economics. Section III outlines the $SCOE$ methodology that is demonstrated in section IV. Section IV also demonstrates an application of the reverse $LCOE$ methodology put forward by [8]. The reverse LCOE methodology provides estimates of the gross spend on WEC cost centres. The results of the case study are discussed and concluded in sections V and VI respectively.

II. BACKGROUND

A number of studies have suggested that $LCOE$ does not provide a true reflection of the cost of energy because it ignores externalities to which cost can be attributed [2], [9]–[11]. These studies have identified a number of external aspects that can have both positive and negative impacts on the cost of energy. The externalities cited in [10] and [11] are presented in Figure 1. Both [10] and [11] present a methodology in which the externalities presented in Figure 1 are quantified and added to calculate an alternative net $LCOE$. The studies undertaken by [10] and [11] sum $LCOE$ with cost of subsidies, transmission costs and variability costs to obtain a, "true cost of electricity [10]." This true cost of electricity value is then summed with monetary values attributed to social cost, economic effects and geopolitical impacts to obtain a macro-economic cost of electricity termed, "society's cost of electricity [10]."

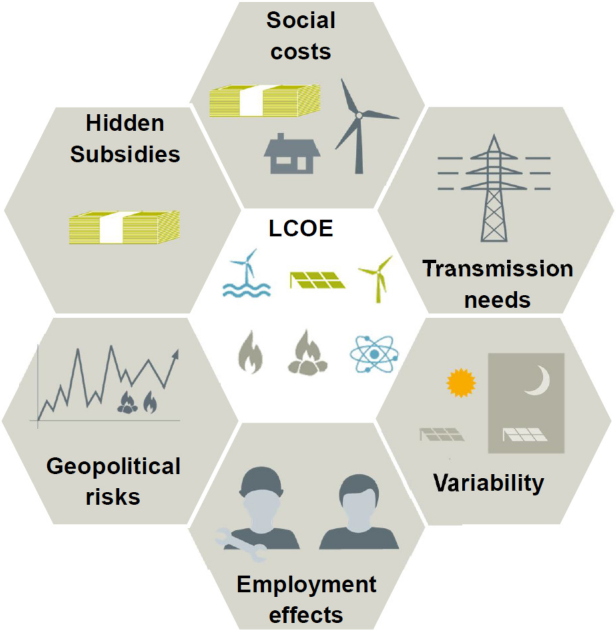


Fig. 1. Externalities considered by [10] and [11].

These studies then go on to compare several energy generation technologies including: Nuclear, coal, gas, solar pv, onshore wind and offshore wind. Both [10] and [11] are helpful for highlighting the different externalities that could be considered when comparing energy generation technologies. However, since the authors of both [10] and [11] are commercial entities, it must be considered that their results may be influenced by commercial interests.

$SCOE$ studies have been performed to evaluate the socio-economic effects of energy generation technologies at different geographical scales. Following the previously described methodology, [12] presents comparisons of wind energy generation with Combined Cycle Gas Turbine generation for five different countries. Again, the results presented in [12] may be influenced by commercial interests. The study undertaken by [13] demonstrates how $SCOE$ studies can be undertaken to evaluate the socio-economic impacts of a renewable energy project at multiple scales whereas the focus of [14] is on a collection of smaller regions within Scotland.

$SCOE$ studies can be performed in a number of ways. These include: analytical studies [15], Input-Output (IO) table based studies [11], [13] and those based on the Computable General Equilibrium, CGE, approach [16]. The IO table based approach is employed in the OPERA project and presented in this paper.

Analytical studies have the benefit of being more transparent than the IO table approach. This means that it is easier to diagnose how different factors influence the outputs of analytical studies. However, the IO table approach does estimate the indirect and induced effects that are the result of an intervention whereas analytical models in general, only calculate direct effects [15].

The IO model approach requires three assumptions to be made, they are as follows:

- The first assumption is that the supply side of the economy is entirely passive meaning that it responds immediately to demand; supply constraints do not effect demand.
- The second assumption is that the intervention analysed with the IO model takes all supply regardless of other external demands.
- The third assumption is that the inputs of each industrial sector represented in the IO table are linearly related to changes in output. This is a result of assuming fixed technical coefficients for each of the industrial sectors represented [17].

The CGE approach does not rely on these three assumptions as it details both demand and supply sides of the economy [18]. Both [19] and [18] use the AMOS framework [16] to run their CGE models. Despite both [17] and [18] highlighting that the IO methodology tends to overestimate number of jobs created relative to the CGE methodology, the IO methodology is used in the OPERA project as it is relatively straight forward to perform and has been used widely in other $SCOE$ studies.

Economic and socio-economic studies are often performed separately [17]. The review undertaken by [17] observed that socio-economic assessments, including environmental studies, are most often the concern of public bodies with input from developers whereas economic assessments, such as $LCOE$ studies, are performed by and for the developers. [17] highlights how both types of analysis are connected and should be considered together.

As stated, the overall economic model that is being developed for the OPERA project comprises $LCOE$, LCA and $SCOE$ streams. This paper presents the methodology undertaken to achieve the $SCOE$ analysis.

III. METHODOLOGY

The $SCOE$ methodology used in the OPERA project, and presented in this paper, estimates job creation and Gross Value Added (GVA) in a chosen geographic region due to the deployment of a WEC project. The job creation figures estimated through the presented methodology are the sum of direct, indirect and induced jobs. Direct jobs are those created within the project developer to undertake the project. Indirect jobs are those created in the supply chain to meet the increased demand of the project developer. Induced jobs are those created in the region of interest due to the increased spending of employees throughout the supply chain [20].

GVA is a measure of the economic impact of an intervention; undertaking of a project. It indicates the contribution to a region's economy that is due to some specific economic activity [21]; in this case, it is the spend that is invested in the region of interest that is due to a WEC array's deployment and operation.

The following sections set out the steps that are undertaken in the $SCOE$ methodology to estimate job creation and GVA.

A. Scenario description

For $SCOE$ studies to produce credible results, they must either be undertaken on large scale projects or used to analyse conceptual deployment scenarios. Although the OPERA project will achieve the significant milestones in terms of device deployment, the installation of a demonstration device with cost reducing innovations will not significantly affect job creation or GVA of a region; that is not the intention of a demonstration project. A conceptual deployment scenario must be developed for analysis.

To undertake an $SCOE$ study, a scenario for analysis must include:

- A deployment location and region for analysis,
- Gross project spend and how the spend is distributed amongst the project's cost centres (the cost centres considered in OPERA and this paper are are manufacturing, installation, operation and decommissioning),
- Project operational plans (estimates on deployment dates and operation periods) and,
- Where cost centre activity will occur.

The deployment scenario analysed within OPERA will be based on information provided by OPERA project partners and lessons learned through the two deployments of Oceantec's MARMOK device [22].

The deployment scenario analysed in the this paper's case study is not related to the OPERA project. The characteristics of the WEC used in the case study (a heaving buoy) and the project spend are based on values obtained from literature and the project operational plans are estimated. The case study is described in detail in section IV.

In both the OPERA project, and the case study presented in this paper, the primary region of interest for analysis is the region in which the WEC project will be deployed. Once a region has been chosen and project spend is known, the modeller must identify how the gross spend on each project cost centre, GS_{cc}, influences the region of interest. This is achieved by determining and using ready reckoners.

B. Ready Reckoners

Ready reckoners are used to calculate the net spend on each of the project's cost centres in the region of interest, NS_{cc}, see Equation (1). In this instance, net spend on a cost centre is the spend on that cost centre that directly benefits the region of interest.

$$NS_{cc} = GS_{cc}\left[(1-L)\left(1-D_w\right)\left(1-D_p\right)(1-S)\right] \tag{1}$$

The ready reckoners in Equation (1) are: Leakage (L), Deadweight (D_w), Displacement (D_p) and Substitution (S).

Leakage reflects how much of the project spend is invested in the region of interest. A high Leakage value indicates that a large amount of project spend is invested outside the region of interest whilst a low Leakage value indicates that a large amount of project spend is invested in the region of interest.

Deadweight accounts for the fact that project activity may prevent alternative additional economic activity from occurring in the region of interest. A high Deadweight value would indicate that alternative investment would have been made in the area were the project not undertaken. A zero Deadweight value indicates that were the project not undertaken, additional spend would not have been invested in the region of interest.

Displacement and Substitution ready reckoners are similar and therefore occasionally grouped together into one ready reckoner [13]. Displacement accounts for industry activity in the region of interest shifting from existing work to work required for the project. A high Displacement value would indicate that the project takes a large market share from existing firms in the region of interest, whereas, a low Displacement value would indicate that the project's needs could be met without taking large levels of existing capacity.

Substitution is used to indicate how existing industry might change their operations to better serve the project. A high Substitution value would indicate that the project requires a large number of industries in the region of interest shift their focus from their existing operations to those of the project's. A low Substitution value would indicate that the project does little to affect the focus of existing industries in the region of interest [23].

It should be stressed that net spend in the region of interest should be calculated for each of the project's cost centres. For example, spend on manufacturing could largely be invested outside the region of interest, therefore indicating a high level of Leakage. However, spend on operation could largely be invested within the region of interest, therefore resulting in a low Leakage value.

Once a net spend has been calculated for each cost centre, coefficients are obtained to estimate how the net spend relates to job creation and GVA. The next section describes how these coefficients are obtained.

C. Job Creation and GVA Calculation

The method presented in this section yields coefficients, termed "effects", that relate the net spend on the different cost centres to job creation and GVA in the region of interest. Effects relate a change in demand, of one unit of currency in a particular industry, to job creation throughout the supply chain and GVA in the region of interest. An effect is specific to the industry it is calculated for. Therefore, effects used in the calculation of job creation and GVA, due to the spend in a particular cost centre, should be associated with the industry (or industries) that will perform activities for that cost centre.

Two types of effect can be calculated; type I and type II. Type I employment effects estimate job creation figures that are the sum of direct and indirect jobs. Type I GVA effects estimate the GVA to the region of interest that is due to the spend of industries in their supply chains.

Type II employment effects estimate a job creation figure that is the sum of direct, indirect and induced jobs. Type II GVA effects estimate the GVA that is due to both the economic activity in the supply chain and the economic activity that is driven by the spend of employees throughout the supply chain. Type II effects are calculated for OPERA and the case study presented in this paper.

Job creation and GVA effects are obtained through the manipulation of Industry by Industry (IxI) IO tables. The IxI IO tables, also termed industry by industry analytical tables, are derived from Supply and Use tables [24] and indicate the output is required from industry i for one unit output from industry j. Note, since the table is symmetric, the same industries are present in the "Industry" columns (j) and the "Product" rows (i) of the IxI IO table.

Effects are obtained through the generation of inverse Leontief matrices. Equation (2) is used to calculate a type I inverse Leontief matrix.

$$\boldsymbol{L_I} = (\boldsymbol{I} - \boldsymbol{A_I})^{-1}, \tag{2}$$

$\boldsymbol{I}$ is an identity matrix and $\boldsymbol{A_I}$ is termed direct requirements matrix. When calculating type I effects, the direct requirement matrix is the IxI IO matrix with each row of every column is divided by the corresponding column's total. In the tables analysed this column total has either been termed, "total output at basic prices [25]," or, "production at basic prices [26]."

When calculating the type II Leontief inverse matrices, the direct requirement matrix, $\boldsymbol{A_{II}}$, is the type I direct requirements matrix ($\boldsymbol{A_I}$) with the addition of an extra column and row that seek to account for employee activity; see Equation 3.

$$\boldsymbol{A_{II}} = \begin{bmatrix} \boldsymbol{A_I} & \boldsymbol{A_{IH}} \\ \boldsymbol{A_{HI}} & 0 \end{bmatrix} \tag{3}$$

Each cell of the $\boldsymbol{A_{IH}}$ column vector is the amount of industry i required per unit of total household income. Total household income is the sum of all the column values in row i, divided by a figure that represents household income. Opinion is divided on the how to calculate total household income [27] as it is difficult to account for unearned income (pensions, dividends, etc.) in the available economic figures. The approach taken here is referred to by [27] as, "M+B(1985)" [28]. This approach divides the sum of all the columns in the row by household income from all sources. This method was chosen since no additional information, from outside the IxI IO table, is required. This approach is the simplest method of estimating household consumption. It is the sum of the "compensation of employees" [25] (referred to as "Salaried renumeration" in [26]). However, this method does tend to overestimate effects.

Each cell of the $\boldsymbol{A_{HI}}$ row vector is the "compensation of employees" figure stated in the corresponding column divided by the column total.

The job creation and GVA effects are calculated through equations (4) and (5) respectively.

$$E_{eff,j} = \sum_i w_i L_{i,j} \tag{4}$$

$$G_{eff,j} = \sum_i g_i L_{i,j} \tag{5}$$

$E_{eff,j}$ in Equation (4) is the employment effect for industry j that is used to calculate job creation. w_i is the Full-Time Equivalent (FTE) employment for industry i divided by column total of the same industry ("total output at basic prices," or, "production at basic prices"). FTE may have to be obtained from other sources. FTE data is provided with the IxI IO table used in OPERA [26]. $L_{i,j}$ is the cell of the type II inverse Leontief matrix that corresponds with industries i and j.

$G_{eff,j}$ in Equation (5) is the GVA effect for industry j. g_i is the GVA of industry i, in the region of interest, divided by column total of the same industry. GVA is typically presented in the IxI IO tables.

As stated, Job creation and GVA estimates, Jb_{cc} and GVA_{cc} respectively, are obtained for a particular project cost centre by multiplying the net spend on that cost centre, NS_{cc}, by the employment and GVA effects that are specific to the industry that will undertake activity for that cost centre.

$$Jb_{cc} = NS_{cc} E_{eff,j} \tag{6}$$

$$GVA_{cc} = NS_{cc} G_{eff,j} \tag{7}$$

Since cost centre activity is likely to be staggered throughout the project (manufacturing will occur the start of the project, decommissioning will take place at the end), it is more appropriate to calculate job years created by a project [17]. Job years are obtained by multiplying the net spend on a cost centre in a given year by the appropriate employment multipliers.

The outputs of the entire methodology are therefore estimates of job creation, in terms of number of job years created, and GVA, either annual GVA or total GVA.

The next section of this paper presents a case study that demonstrates the use of the described methodology.

IV. CASE STUDY

This section presents a case study that demonstrates how the $SCOE$ methodology described in section III is used to calculate job creation and GVA in a region of interest. It also presents an application of the reverse $LCOE$ methodology set out by [8].

Recall, as stated in section III, the WEC and project deployment plan presented in this case study are not related to the OPERA project. The heaving buoy WEC characteristics, the project spend and operational plans are estimated and based on values taken from literature.

The case study estimates job creation and GVA in the Basque Country that is due to the deployment of an array of heaving buoy WECs at *BiMEP*. The deployed array has a rated power, P, of $10\,\mathrm{MW}$.

The following assumptions are made at the outset of the case study:

- For the project to go ahead, it is assumed that it is economically viable. It is therefore assumed that the project achieves an $LCOE$ of $150\,\text{£}\,\mathrm{MWh}^{-1}$. This $LCOE$ value is in line with the targets set by Wave Energy Scotland (WES) [29] in its funding calls.
  Note, achieving this target in 2017 would mean that the WEC was economically viable when compared with other energy generation technologies. However, this is not a fixed target and will lessen with advances in other competing industries. It is likely that by the time WECs become economically viable, they will have had to achieve a lower LCOE than the target set here.
- The heaving buoy WECs in the array have a characteristic dimension, D, of $12\,\mathrm{m}$ (this is the diameter of the buoys) and Capture Width Ratios (CWRs) of $16\,\%$. These characteristics are based on mean values obtained from [30].
- The availability of the WEC, ϵ, is assumed to be dependent only on the significant wave height for which the device enters into survival mode. Here, it is assumed that the device will enter survival mode in sea states with significant wave heights greater than $5\,\mathrm{m}$. According to Figure 1 of [31], conditions at the *BiMEP* site mean that the WEC will have an availability in the region of $97\,\%$.
- The *BiMEP* site has been measured to have an average resource, J, of $21\,\mathrm{kW\,m^{-1}}$ [32]. It is assumed that this resource is constant every year of the project.
- It is assumed that the yearly financial outgoings of the project will be influenced by an inflation rate of $2\,\%$.

The case study array deployment and operation is undertaken in four phases, see Figure 2. Each phase manufactures, installs, operates and decommissions an equal number of WECs. The phases are staggered to account for capacity in the manufacturing of the WECs. Each device operates at sea for $25\,\mathrm{years}$.

For clarity, the case study will proceed as follows:

- The reverse $LCOE$ methodology is used in section IV-A to obtain an overall project cost threshold that must be adhered to in order to ensure the WEC project is economically viable (achieving a target $LCOE$ of $150\,\text{£}\,\mathrm{MWh}^{-1}$). The overall project cost threshold that is calculated using the reverse $LCOE$ methodology is then broken down into cost centres based on cost breakdown percentages obtained from [33].
- The $SCOE$ methodology is then presented in section IV-C.
- Approximated ready reckoners, Table I, are then used to calculate the net spend on each WEC project cost centre in the region of interest.
- Approximated effects, Table II, are then used to calculate job creation and GVA due to net project spend in each of the WEC project cost centres in the region of interest.

A. Reverse LCOE

The reverse $LCOE$ method starts with a target $LCOE$ [8]. This $LCOE$ value is used to determine a total cost threshold that must be adhered to in order for a project to achieve the target $LCOE$. The reverse $LCOE$ method is used in this case study to estimate how project spend is distributed amongst project cost centres. As stated, the target $LCOE$ value in this study is set at $150\,\text{£}\,\mathrm{MWh}^{-1}$.

A total project cost threshold is obtained by multiplying the $LCOE$ equation, Equation (8), by the summation of the discounted Annual Energy Production (AEP) generated during each year of the project's operation to obtain a total project cost threshold, Equation (9).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t + DECOM_t}{(1+r_R)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r_R)^t}}, \tag{8}$$

$$\sum_{t=1}^{n} \frac{AEP_t}{(1+r_R)^t} \times LCOE = \ldots$$
$$\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t + DECOM_t}{(1+r_R)^t}, \tag{9}$$

$CAPEX$ in Equations (8) and (9) is the Capital Expenditure, $OPEX$ is the Operational Expenditure and $DECOM$ is Decommissioning expenditure. Both manufacturing and installation costs are contained within the $CAPEX$. The summation of these discounted costs is the total cost of the project. n is the number of years in the project and r_R is the discount rate. r_R is taken to be $10\,\%$. This value is chosen as it is the average between the values used in [34] and [33]. The $10\,\%$ discount rate acknowledges the return on investment expected for a high risk project.

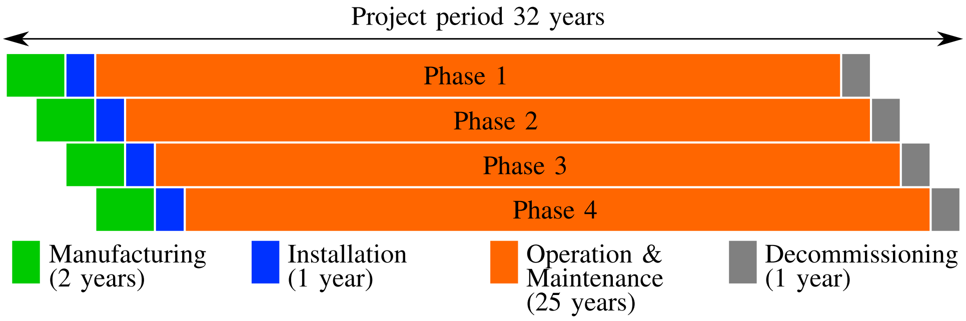


Fig. 2. Case study project time line.

Following the reverse $LCOE$ methodology, calculation of AEP initially requires a calculation of the number of WECs in the project's array, N, see Equation (10).

$$N = \frac{P}{CWR \times D} \tag{10}$$

Calculating the number WECs with this equation means that no assumptions are made about the devices Power Take-Off (PTO). Since the array rating (P) is $10\,\mathrm{MW}$, the site resource (J) is $21\,\mathrm{kW\,m^{-1}}$ and each devices' capture width (D) is $12\,\mathrm{m}$, Equation (10) indicates that forty WECs will be deployed in the overall WEC array. Therefore ten devices are deployed and operated in each phase; recall that the project is being undertaken in four phases.

AEP, of the array is calculated using Equation (11).

$$AEP = \frac{\epsilon \times CWR \times D \times J \times N \times 8766\,\mathrm{h}}{1000} \tag{11}$$

N is the number of WECs in the array. The figure of $8766\,\mathrm{h}$ in the numerator is the number of hours in a year whilst the value of 1000 in the denominator converts the AEP value from kWh to MWh. Equation (11) indicates that the array, when fully operational, will have an AEP of $13{,}605\,\mathrm{MWh}$.

Note, the case study assumes that each operational WEC yields the same AEP every year. Due to the staggered nature of deployment and retrieval, the array is only fully operational from project years seven to twenty-eight. Fewer WECs are operational from project years 4 to 6 (10, 20 & 30 WECs) and 29 to 31 (30, 20 & 10 WECs).

B. Reverse LCOE results

As stated, the result of the reverse $LCOE$ procedure is a total cost threshold for the project, that is, the maximum cost that can be subdivided between $CAPEX$, $OPEX$ and $DECOM$ activities. The total cost threshold is calculated to be £ 12,132,000. This value is converted into Euros using an exchange rate of 1.2 [35]; this yields an available spend, at present values, of $14{,}558{,}000\,€$.

The next step in the reverse $LCOE$ method is to subdivide the total threshold into different WEC cost centre thresholds. This procedure dictates the permitted spend on each of the cost centres throughout the life of the project. In this case study, the cost breakdown is guided by the percentage of lifetime cost figures presented in [33]. The cost breakdown set out in [33] is depicted in Figure 3.

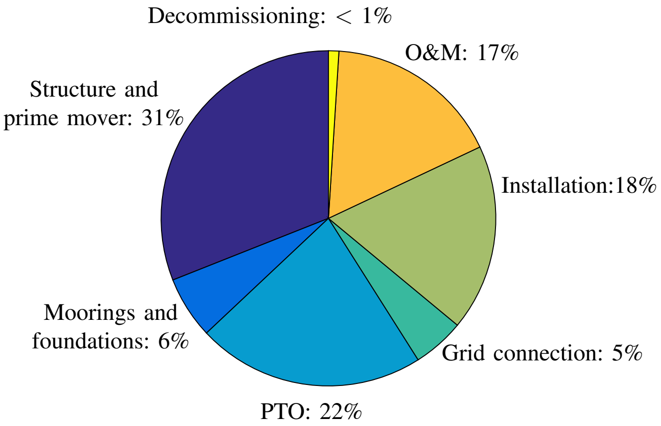


Fig. 3. WEC cost breakdown [33].

Based on the total project threshold value of $14{,}558{,}000\,€$, calculated using the reverse $LCOE$ method, and the cost breakdown percentages obtained from [33], the case study's cost breakdown is as follows:

- Structure and prime mover = $4{,}513{,}000\,€$,
- PTO = $3{,}203{,}000\,€$,
- Grid connection = $728{,}000\,€$,
- Moorings and foundations = $873{,}000\,€$,
- Installation = $2{,}620{,}000\,€$,
- Operation and Maintenance (O&M) = $2{,}475{,}000\,€$ and,
- Decommissioning = $146{,}000\,€$.

As stated in section III, four cost centres are considered within this study. They are: manufacturing, which includes structure and prime mover, PTO, grid connection and mooring and foundation costs; installation; operation, which includes O&M costs; and decommissioning.

There are a number of sources of uncertainty in the reverse $LCOE$ approach. For example, using cost breakdown percentages takes no account of the approaches taken by specific WEC developers i.e. WEC developers take different approaches, or employ different innovations, to reduce costs in certain cost centres to spend more in others. In addition to this, WEC cost centre percentages vary depending on the device class chosen. The cost centre percentages set out in [33] were chosen as that study was non device specific and intended to provide a general summary for the overall industry. Additionally, the reverse LCOE methodology assumes that the overall reduction in LCOE is due to equal cost reductions in each cost centre. In reality, this is not likely to be the case as some cost centres are more likely to reduce in cost than others. Other uncertainties are contained within the AEP calculation, such as those associated with the availability, reliability and accessibility etc.

However, the reverse $LCOE$ methodology set out in [8] is useful for early stage developers to guide them on how to balance costs of a project. Further to this, the primary aim of this case study is to demonstrate how to implement the $SCOE$ methodology and therefore accuracy of the final figures is not crucial.

C. *Socio-Economic Cost of Energy*

The cost centre thresholds calculated through the reverse $LCOE$ method are the gross values that can be spent on the individual project cost centres. Ready reckoners, discussed in section III-B, are used to estimate the net spend on each of the cost centres in the Basque Country. Table I shows the ready reckoners that are approximated for the case study. Refer to section III-B for definitions of the ready reckoners listed in table I.

TABLE I
CASE STUDY APPROXIMATED READY RECKONERS

Ready Reckoner	**Manufacturing**	**Installation**	**O&M**	**Decommissioning**
Deadweight	0%	0%	0%	0%
Leakage	75%	50%	10%	50%
Displacement	0%	0%	0%	0%
Substitution	0%	0%	0%	0%

The majority of the ready reckoners used are $0\,\%$. This is because of the relatively low spend of the project. The values spent in the project are low relative to the overall value of the industries in the Basque Country that will potentially be involved in the deployment and operation of the WEC array. For example, the maximum present value of O&M activities in one year is 62,000 €. If it is assumed that fishing vessels are employed to carry out O&M activities, there is potential for Displacement or Substitution. In the Basque Country in 2014, the production at basic prices of fishing and aquaculture industry was 384,760,000 € [26]. This indicates that, although there is potential for the project to cause Displacement and Substitution in the fishing and aquaculture industry, the project spend is too low to have a notable effect on the local industry. Deadweight is also zero, i.e. were the project not undertaken, no added economic activity would have occurred in the region.

Leakage values are nonzero as it is acknowledged that spend will be invested outside to the Basque Country. Note, the Deadweight, Displacement and Substitution ready reckoners account for impact of spend in the deployment region whilst Leakage determines the amount of spend that reaches the region. Considering the capacity of the deployment region and its accessibility to surrounding regions (Spain), it seems reasonable to assume that during the manufacturing phase of the project, Leakage will be very high, approximately $75\,\%$ [23]. For the installation and decommissioning phases, Leakage has been set to $50\,\%$. It is assumed that specialist vessels and their crews will be sourced from outside the Basque Country for specific activities within these phases. Leakage is set to be low during the O&M phases as it is assumed that contractors stationed within the Basque Country can be utilised to undertake the majority of O&M activities. A small amount of leakage is expected due to activities that might occur outside the region. The split in where the case study's project spend is invested is shown in Figure 4. After leakage, the spend invested by the project in the Basque Country is estimated to be 4,646,000 €.

As stated, it is assumed that the yearly financial outgoings of the project increase with inflation. The assumed inflation rate of $2\,\%$ determines how much of the net spend, on each of the project's cost centres, can be spent in each year of the project. The inflation rate accounts for the fact that yearly financial outgoings during the latter years of the project will have to increase to achieve the same amount of work. Note, in this case study, the amount of work undertaken in each project year on each activity (person years) is constant throughout the duration of the activity. For example, it is assumed that the same amount of person years will be required for O&M activity in the first and last years of the arrays full operation. Figure 5 shows the yearly financial outgoings of the project. The required increase in spend, to achieve equal person years,

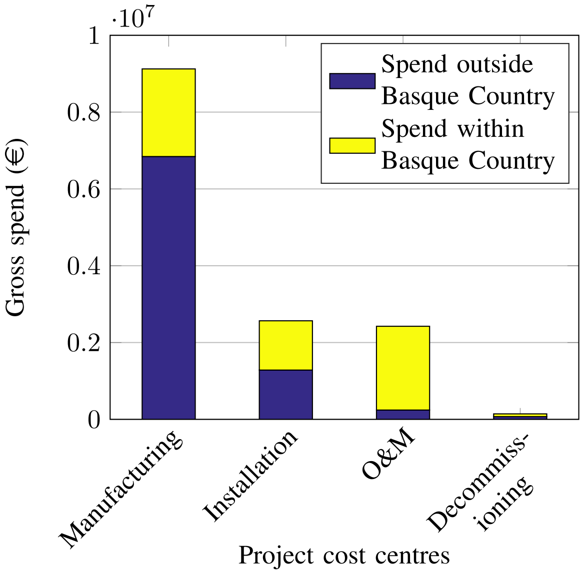


Fig. 4. Split of project spend for each cost centre within and outside the Basque Country.

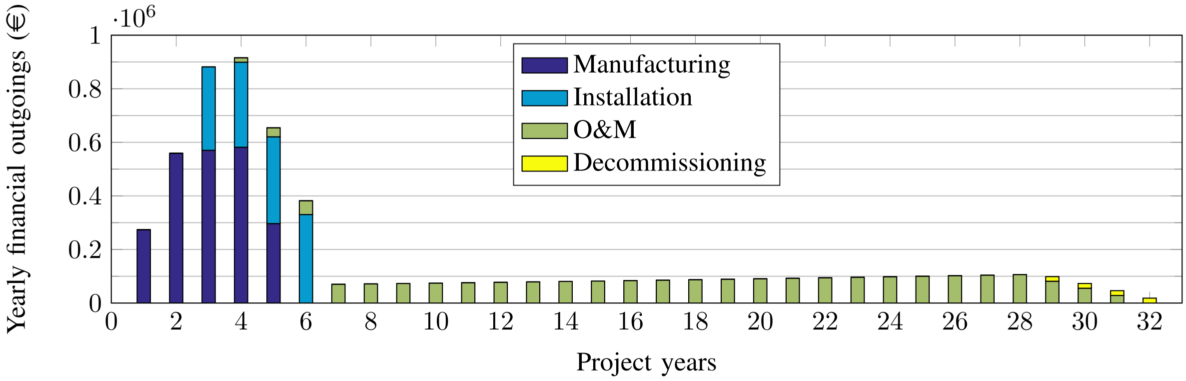


Fig. 5. Yearly financial outgoings in the Basque Country in each WEC cost centre for each year of the project.

is most notable in the O&M spend. Figure 5 shows the yearly financial outgoings of project in year twenty-eight to be greater than in year seven despite the fact that during both years, O&M activities are undertaken on all forty devices in the array.

IxI IO tables were obtained for the Basque Country from [26]. The tables used are the most up to date and correspond to 2014. A type II inverse Leontief matrix was obtained using the approach set out in section III-C. As described, the matrix was used to obtain employment and GVA effects for each of the industries represented by the IO tables.

Since the industries involved in the manufacturing, installation, O&M and decommissioning of WECs are not clearly represented in the IxI IO tables, the effects for similar industries were averaged. The following list indicates the industries that were averaged to obtain the effects used in the case study.

- Manufacturing - Metal construction, Metal forging and pressing, Mechanical engineering, Computer products & electronics, Electrical equipment, Ship building, Information technology and Architectural and engineering services.
- Installation - Repair & installation, Construction, Other goods transport by road, Maritime & watercourse transport and Support activities for transport.
- Operation & Maintenance - Mechanical engineering, Computer products & electronics, Electrical equipment and material, Repair & installation, Sale & repairs of vehicles, Maritime & watercourse transport, Support activities for transportation and Information technology.
- Decommissioning - Mechanical engineering, Computer products & electronics, Electrical equipment & material, Repair & installation, Construction, Other goods transport by road, Maritime & watercourse transport and Support activities for transport.

Table II shows the employment and GVA effects obtained for each of the cost centres. The standard deviation of the effects averaged are also shown to indicate the uncertainty in these figures.

TABLE II
ESTIMATED EMPLOYMENT AND GVA EFFECTS PER 1,000€.

Activity	**Employment effect**		**GVA effect**	
	Average	STD	Average	STD
Manufacturing	0.014	0.005	0.96	0.27
Installation	0.014	0.004	1.03	0.17
O&M	0.015	0.005	1.01	0.22
Decommissioning	0.014	0.004	1.00	0.18

D. *Socio-Economic Cost of Energy Results*

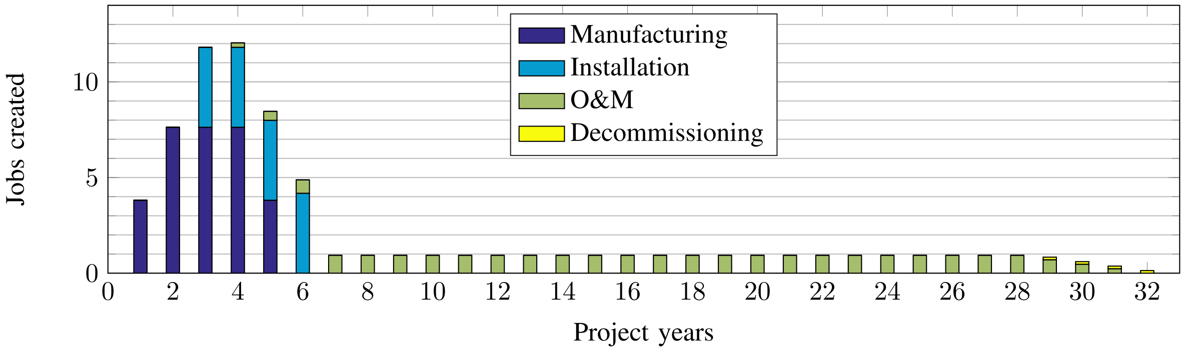
The employment effects presented in Table II were multiplied by the present value of the net spend invested in each year of the project on the corresponding cost centres. This step yielded the job years created by each of the project cost centres which can be summed to obtain the total job years created by the project in a single year. This is shown on Figure 6(a). The job years created by the project each year can be summed to obtain the overall job years created by the project. In total, it is estimated that seventy-one job years are created by the case study project. The majority of jobs being created during the manufacturing and installation phases.

Similar steps can be followed to calculate the GVA created by each cost centre during each year of the project. Figure 6(b) presents the total GVA created by the project in each year of the project. The total GVA to the Basque Country, at present values, due to the project is estimated to be $4{,}948{,}238$ €.

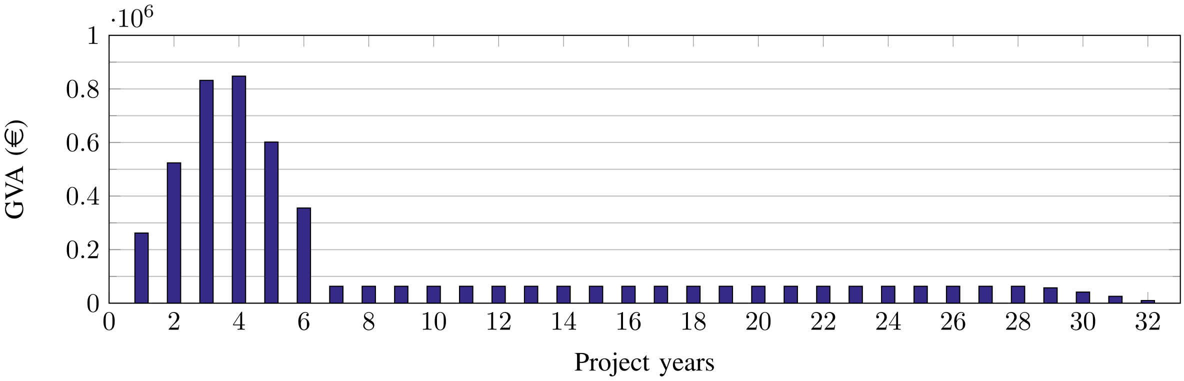
V. DISCUSSION

The case study presented in section IV demonstrated how the reverse $LCOE$ method developed by [8] can be used to estimate cost centre thresholds for an economically viable WEC. It also provided a demonstration of the $SCOE$ methodology, showing how job creation and GVA can be estimated.

As previously stated, there are a number of sources of uncertainty within the case study, however, it still has value as a demonstration of the two methodologies presented. When employed by developers, and with increased experience in the



(a) Job creation in the Basque Country.



(b) GVA in the Basque Country.

Fig. 6. Case study results.

industry, the uncertainty will be much reduced. The aforementioned uncertainties contained within cost centre threshold estimates will be reduced because developers will have a good understanding of the cost centres of their devices. Furthermore, developers will have knowledge of where their devices will be manufactured and where their operational activities will occur, thus enhancing the accuracy of the ready reckoners used. Developers will also have more sophisticated methodologies for estimating AEP and O&M costs and plans. Uncertainty in the effect multipliers used will reduce with increased deployment and operation of marine renewables. It is anticipated that lessons will be learnt from the deployment and operation of both offshore wind and tidal devices.

The GVA to the region (4,948,238 €) was calculated to be greater than the estimated net spend (4,646,000 €). This is due to the GVA effects for the Installation and O&M activities being greater than one; see Table II. The GVA effects for these activities are greater than one because a large portion of the spend of the industries involved, and their employees, is reinvested in the Basque Country.

Figures 5, 6(a) and 6(b) show a large spike in yearly financial outgoings, jobs created and GVA during the early years of the project. This was also presented in [13]. The spike corresponds to the manufacturing and installation activities. This is due to the large spend associated with these activities. The cost centre percentages used estimate that 82 % of the project spend occurs at the start of the project, see Figure 3 and [33].

Unlike [13], there is not a spike in yearly financial outgoings, job creation and GVA at the end of the project. This is again due to the financial outgoings during this period of the project. Figure 6(a) indicates that 0.14 job years are created by the decommissioning of ten WECs. Further to this, Figure 6(a) also indicates that from project years seven to twenty-eight, one job year is created each year for the O&M of forty WECs. These job year figures are unlikely. Recall, using type II inverse Leontief matrix effects mean that the estimates of job creation include direct, indirect and induced jobs. These observations highlight the challenge of using cost centre percentages in the reverse $LCOE$ method and how the $SCOE$ method can be used as a tool to sanity check values forecast for project cost breakdowns.

Aside from redistributing costs within the project, an alternative approach to increasing the number of jobs created, to make activities feasible, would be to increase the spend on the project. This would mean that the WEC project was no longer economically viable; $LCOE$ would increase above $150\,£\,\mathrm{MWh}^{-1}$/$180\,€\,\mathrm{MWh}^{-1}$. However, if a developer could demonstrate that a non-economically viable project benefited the deployment region's local economy in terms of job creation and GVA, then it could still incentivise funding. This is also a pertinent point considering the current state of the industry.

At present, no WECs have reached the stage of economic viability. The $SCOE$ methodology presents developers with a tool with which evaluate how their projects benefit local economies. Developers could use the $SCOE$ methodology to plan how to undertake operations in a way that would benefit local economies, thereby increasing the likelihood of positive local engagement and making their projects more attractive for investment.

In addition to this, it is conceivable that the $SCOE$ methodology could be used as a tool by funding bodies to incentive developers to carefully consider the alternative benefits of WEC deployments.

VI. CONCLUSIONS

This paper has presented an $SCOE$ methodology that estimates job creation and GVA due to the deployment of an array of WECs. A case study enabled the demonstration of both the reverse $LCOE$ methodology, which estimates cost centre thresholds for an economically viable WEC array, and the $SCOE$ methodology.

The results of the case study presented in this paper have shown how the $SCOE$ methodology can be used to sanity check cost estimates calculated at an early stage of a WEC project's development.

Previous studies have shown how the $SCOE$ methodology can be used to compare energy generation industries with one another. The paper suggests that the methodology could be used at a lower and more detailed level to plan WEC project development pathways. Developers could use the $SCOE$ methodology as a tool to plan project deployments to benefit local economies. Benefiting local economies could have the effect of improving public engagement and could potentially make marginally non-economically viable WEC projects more attractive to funding bodies. Alternatively, funding bodies could use the $SCOE$ methodology to encourage WEC project developers to consider further social impacts of their projects.

ACKNOWLEDGMENT

The work presented in this paper was undertaken as part of a project that has received funding from the *European Union's Horizon 2020 research and innovation program* under grant agreement No. 654444.

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