Operational expenditure costs for wave energy projects and impacts on financial returns

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1 Nomenclature

OPEX	Operational expenditure
CAPEX	Capital expenditure
WEC	Wave energy converter device
O/M	Operation and maintenance
IC	Initial cost
IC_{wec}	Initial cost of the WEC
TIC	Total initial cost of the project
AEO	Annual energy output
FIT	Feed-in tariff
COE	Cost of electricity
NPV	Net present value
IRR	Internal rate of return

2 Introduction

This paper examines 'availability' and the input metrics of operational expenditure (OPEX) for wave energy projects (assuming *early stage* technology), and reports on a case study which assesses the impact of these inputs on project profit returns.

Assessment and calculation of OPEX has been a very important study area for onshore wind [1]. The determination of OPEX and its mitigation has been one the reasons for the increase in onshore wind installations in Europe and globally [2, 3]. Research into offshore renewable OPEX has been negligible to date, with only a few reports quoting costs, with little or no analysis (a review of the reports is discussed in the next section).

The object of the paper is threefold:

- Discuss access and availability with respect to weather windows and impact on energy output and wave farm operations.
- Define input metrics to calculate OPEX of wave energy projects.
- Assess impact of OPEX on net present value (NPV) and internal rate of return (IRR).

A case study method was used to examine the above objectives modelling a 75MW wave energy project at two locations; the west coast of Ireland and the north coast of Portugal. The model used for the analysis in this paper was NAVITAS, which is a Microsoft Excel [4] tool developed by the Hydraulics and Maritime Research Centre (HMRC)[1] under the Charles Parsons research award.

[1] http://www.ucc.ie/research/hmrc/

The wave energy converter (WEC) chosen for analysis in this report was the Pelamis P1, as it is the only WEC to date that has a published power performance matrix and has preliminary initial cost estimates published by the EPRI study [5]. A further report by EPRI was conducted 2 years later (2006) by Bedard [6]. The reliability of the Pelamis power matrix has never been fully verified since it was first published in 2003, and unfortunately, there has been no update of the matrix since. There have also been no revised initial costs estimates for the Pelamis device, nor has the company volunteered to provide up to date costs. Therefore, the Pelamis device, it's matrix and costings, are only used in the context of a case study and provide a platform methodology to examine the paper's research aims.

Revenues used for the simulations were based on a feed-in tariff (FIT) of €0.30/kWh at both locations. This figure was recommended from a previous paper by Dalton et al. [7] as a feed-in tariff that would provide an attractive IRR and financial return for an Irish location.

Results extracted from this study must be taken as indicative and relative, keeping in mind that the main focus of the paper is a sensitivity analysis of the impacts of OPEX on wave energy project returns.

3 Literature review on operation expenditure (OPEX)

3.1 Operation and maintenance

A literature review was conducted inspecting OPEX metrics. The average results determined from that review were used as the inputs for the case study simulations. The review consisted of published reports from onshore wind and offshore wind, as well as wave energy reports.

Operation and maintenance (O/M) is defined in this case study as all annual costs required to maintain optimum mechanical performance of wave farm devices. In this report, it will include all scheduled and unscheduled maintenance. The logistics of these two sub-categories will not be explored in this paper.

Metrics relating to O/M expense are defined in the literature by either of 4 following metrics and statistics, which are also summarised in Table 1:

1. €/MWh: This is the most commonly used metric which provides a cost based on the relationship between the total initial cost of the project and the annual energy output and is the most commonly quoted metric. Its main advantage is

that it can be used as a performance indicator, as the result is directly proportional to the device performance at the location. It can be used as an input cost in cash flow analysis and also can be used to calculate a percentage relationship to the total cost of electricity (COE) per MWh (see paragraph below). However, €/MWh is not the simplest metric as it requires that the total energy output be already calculated. Its disadvantage is that the O/M result is location specific, and will change for the same device used in different locations, which can result in confusion if quoted in reports without qualification.

2. % of initial cost (IC): The next most popular metric is O/M calculated as a percentage of the total initial cost of a project (TIC). The advantage of this method is in its simplicity, and that it is uniform in operation in any location, and thus easier to use in cash flow sheets. It can be used as an input cost in cash flow analysis and the rate can be a variable in sensitivity analysis. The metric has many disadvantages:
    - In a review of the literature where this metric is used, it is often not clear whether % of the initial cost of the device (IC_{wec}) or the total project initial cost (TIC).
    - The metric does not reflect costs specific to a location.
    - The % of IC figure is often arbitrarily chosen for economic analysis and not based on actual evidence.
3. % of the total OPEX. This metric defines O/M as a percentage of total OPEX. The advantage of this metric is that it is useful for comparative analysis. The disadvantage is that it cannot be used as an input cost in cash flow analysis.
4. % of cost of electricity (COE): The final method compares the % O/M cost in €/MWh to the total COE. It requires both the O/M and COE based in €/MWh. The metric is useful if COE forms a major component of cost analysis of a report. The disadvantages of this metric are that it requires that COE be already calculated. The metric consequently cannot be used as an input cost in cash flow analysis.

Wind/ wave	Location	Author	Reference	€/MWh	% of total TIC[a]	% of OPEX	% of COE
Wave	USA	Bedard, Siddiqui	[8, 9]	24			
	USA	Bedard	[10]	19-36			
	USA	Oregon	[11]	16	1.4%		14%
	Europe	Batten	[12]		5%		
	Canada	Dunnett	[13]		2%		
	USA	EPRI	[5]	6	4.5%		
	UK	Carbon Trust	[14]	19[c]	1.5%		
	UK	Carbon Trust	[15]			57%	
OnshoreWind	USA	Bedard	[10]	6			
	USA	Bolinger	[16]	20 (1980)			
	USA	Bolinger	[16]	6 (2000s)			
	Europe	EWEA	[17]				25%
	Germany	Albers	[18]	8-16	1.8-3.6%		
	Europe	EWEA	[19]	40			
	Europe	Lemming	[20]		1-7%		
	Denmark	EWEA/RISO	[1]	5-15-45			
Offshore Wind	Europe	EWEA	[21]	16	3.3%		26%
	UK	Van Bussel	[22]		4-4.5%		
	Netherlands	Rademakers	[23]	8-16			25-30%
	Europe	EWEA	[24]			26%	
	UK	Dale	[25]	3[b]			

Table 1: Literature review of operation and maintenance cost for onshore and offshore wind, and wave energy studies. Four metrics are presented: €/MWh, % of TIC, % of OPEX and % of cost of electricity (COE). [a] % quoted are assumed to be a % of the TIC, although not clearly defined in reports. [b] Result based on $24/kw/yr quoted in the paper. [c] Costs were quoted in $ and have been converted to € at the conversion rate of €1 to $1.5, and [d] Costs were quoted in £ and have been converted to € at the conversion rate of £1 to €1.15 (July 2011)

Onshore and offshore wind have some conflicting results. Both technologies quoted with the same €/MWh, although their % of IC figures differ. It would be expected that €/MWh for offshore wind should be higher than onshore wind due to the higher IC. This anomaly can be explained by the following example and explanation: a 5MW rated wind turbine will be expected to produce a higher energy output in an offshore location than an onshore location, due to an expected higher capacity or load factor. Although a 5MW wind turbine may have similar IC costs for both onshore and offshore applications, the installation and connection costs for offshore will be higher. Accounting for both factors, the higher energy output of the offshore turbine will offset the higher IC costs for that location, producing similar €/MWH results as its onshore equivalent. The higher €/MWh for wave energy implies that wave energy IC is much higher than offshore wind, and are not compensated by the slightly higher energy returns or capacity factor.

3.2 Insurance costs

The costs of insurance in an under-researched area for the whole offshore renewable energy sector. There are 2 main ways of quoting insurance costs for cash flow analysis; % of IC and €/MWh. The Carbon Trust produced two reports quoting insurance. The first reports quotes a list of insurance types and expenses as follows [14]:

- All risk insurance at 2% of IC.
- Cost overrun insurance at 3% of the first year revenue.
- An operational insurance of 0.8% of the IC.
- Business interruption insurance of 2% of energy revenue.

The Carbon Trust report [15] quotes the insurance component of total OPEX at 14%. EWEA quote insurance as 13% of total OPEX [24]. The EPRI report [5] quotes €27MWh and 2% of initial cost for insuring the Pelamis in the Oregon project. The Irish Wind Energy Assoc (IWEA)[2] use another metric, €/MW and "insurance costs typically work out around €15,000 per MW for the development of the project and the first year of operation with a progressive reduction in cost after year one".

3.3 Access and availability levels

Availability is defined as the amount of time the device is on hand to produce power and is affected by a number of factors including device reliability and the ability of the device to be accessed for maintenance [26]. The percentage of time that a device can be accessed is defined in this paper as '% access' [27]. According to O'Connor et al [28], limited access for O/M operations may be a crucial barrier for future wave farm developments in aggressive wave climates such as the Irish west coast due to reduced availability of a device and limited time required to diagnose and repair faults. Lack of access for O/M is already an issue for the offshore wind industry, even in benign wave regimes such as the North Sea [29, 30]. Onshore wind turbines, with 100% access have 'availability' levels of typically 98% or more [31] (Table 2).

[2] http://www.iwea.com/index.cfm/page/planning_regulationsandadminis

Offshore wind farms in the North Sea have ‘access’ levels typically between 60% [27] and 80% [32] based on a wave height access limit of Hs 1.5m. As a result of the decreased levels of ‘access’, offshore wind farms have ‘availability’ levels that are lower than onshore wind. Lyding et al. [26] for example quotes ‘availability’ figures for various offshore wind farms in 2006 and 2007 as between 70 to 90%. In a recent survey by PriceWaterhouseCoopers, offshore wind operators reported typical ‘availability’ levels of 90-97 % [33]. The recent improvement may be as a result of improved access methods allowing maintenance to occur in higher sea states and/or an improvement in turbine reliability.

	Access Levels	**Availability Levels**
Onshore Wind	100%	98% [31]
Offshore Wind	60%[27] – 80%[32]	70-90% [26] 90-97% [33]

Table 2: Summary of typical access and availability levels for onshore and offshore Wind.

The levels of access to wave energy devices are likely to be lower than offshore wind, due to the more aggressive wave climates that the wave devices will be deployed in, as well as the devices themselves not being stationary, making access from floating vessels even more difficult. As a result ‘availability’ levels for wave energy may be lower than 90%.

‘% Access’ is equivalent to ‘non-exceedance’[3] which is also defined as the percentage of the year that the wave heights are below a certain wave height limit. In reality, ‘% access’ would likely be lower than ‘% ‘non-exceedance’’ as ‘non-exceedance’ would include times when the wave heights would be below the access limit but for periods not long enough for certain O/M tasks to be carried out. Also ‘non-exceedance’ figures don’t take account of other factors such as accuracy of prediction, readiness of suitable vessels and other met-ocean constraints such as wind, wave period etc. which would influence access.

[3] ‘Non-exceedance’ graph = Inverse of exceedance graph. An exceedance graph for significant wave height shows the percentage of the time that the wave heights are above a certain wave height value.

4 Methodology and inputs

4.1 Project locations and device

The location for the Irish data was the M4 buoy off Belmullet, 55 deg N, 10 deg W or approximately 25 km off the coast of Mayo, water depth 150m (Figure 1). (M4 buoy was moved from 54 40N, 09 04W to 55N, 10W on 3rd May 2007)

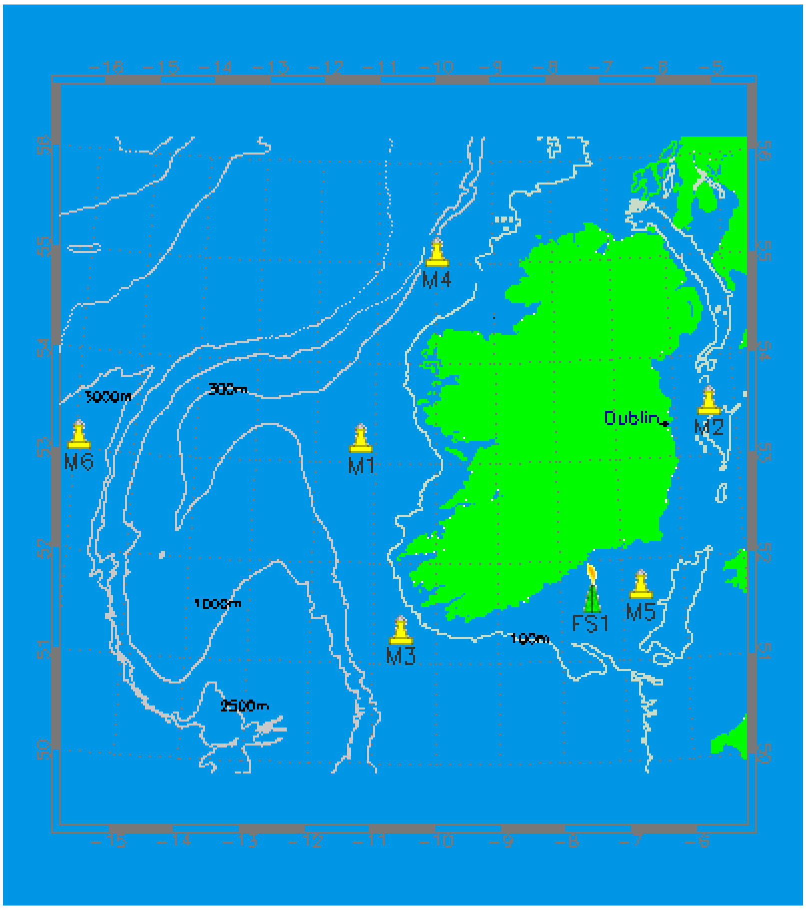

Figure 1: Map of location of the M series buoys around Ireland[4].

The Portuguese data was taken from the Leixoes buoy which is located at 41.31 deg N, 8.98 deg W or approximately 19 km off the coast of Portugal, water depth 83m (Figure 2). Data from 2007 was used at both sites.

[4] http://www.met.ie/marine/MarineWx2005.pdf, http://www.marine.ie/home/publicationsdata/data/buoys/

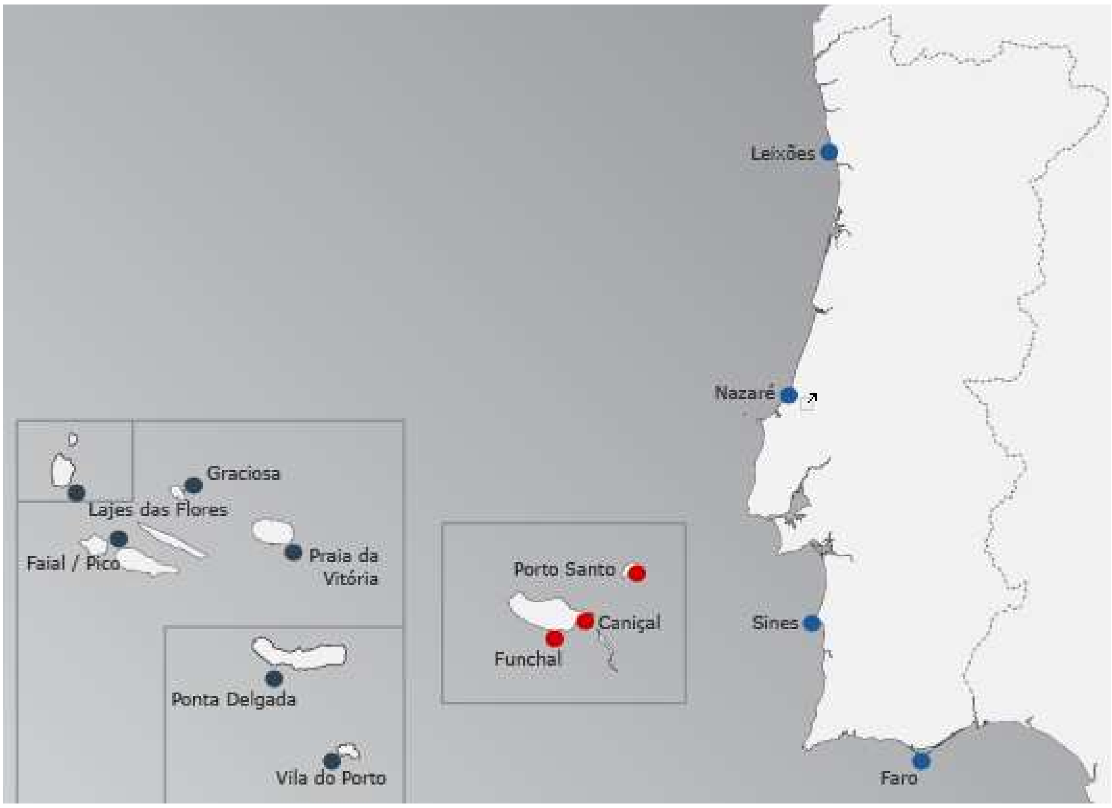

Figure 2 Map of location of Portuguese wave buoy at 'Leixoes' in northern Portugal. [5]

4.2 Pelamis power matrix

The total annual energy output (AEO) for the year was calculated in NAVITAS by multiplying each cell point of the scatter plot of hours with the corresponding cell of a WEC power matrix. The Pelamis power matrix [34] is presented in Table 3. Power peaks at 750 kW for a number of sea states.

Wave energy input (WEI) is calculated using the following Equation 1[6]:

Equation 1 $WEI=0.59Hs^2Tz$

Where Hs is mean significant wave height, and Tz is the mean zero crossing period. The Pelamis scatter plot uses Te, which is the energy in the period, and is calculated from Tz in Equation 2.

Equation 2 $Te = 1.2*Tz$

[5] http://www.hidrografico.pt/boias-ondografo.php
[6] Modified power formula due to recent work at HMRC [36]

	Wave Period (Te)												
Wave Height Hs(m)	1	2	3	4	5	6	7	8	9	10	11	12	13
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	29	37	38	35	29	23	0	0
1.5	0	0	0	0	32	65	83	86	78	65	53	42	33
2	0	0	0	0	57	115	148	152	138	116	93	74	59
2.5	0	0	0	0	89	180	231	238	216	181	146	116	92
3	0	0	0	0	129	260	332	332	292	240	210	167	132
3.5	0	0	0	0	0	354	438	424	377	326	260	215	180
4	0	0	0	0	0	462	540	530	475	384	339	267	213
4.5	0	0	0	0	0	544	642	628	562	473	382	338	266
5	0	0	0	0	0	0	726	707	670	557	472	369	328
5.5	0	0	0	0	0	0	750	750	737	658	530	446	355
6	0	0	0	0	0	0	750	750	750	711	619	512	415
6.5	0	0	0	0	0	0	750	750	750	750	658	579	481
7	0	0	0	0	0	0	0	750	750	750	750	613	525
7.5	0	0	0	0	0	0	0	750	750	750	750	686	593
8	0	0	0	0	0	0	0	0	750	750	750	750	625
8.5	0	0	0	0	0	0	0	0	0	750	750	750	750
9	0	0	0	0	0	0	0	0	0	0	750	750	750
9.5	0	0	0	0	0	0	0	0	0	0	0	750	750
10	0	0	0	0	0	0	0	0	0	0	0	0	750
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3: Power matrix for the Pelamis WEC(Values in kW) [34].

4.3 Access and availability factors

The maintenance strategy of the Pelamis involves the device being disconnected and brought ashore for maintenance, which Pelamis state can be done in seas up to Hs 2.0m [37]. Figure 3 shows the percentage of the year that the wave heights were below a certain wave height limit. For Hs = 2.0m, '% access' levels are 34% for M4 and 68% for Leixoes.

Figure 4 presents an adapted version of Van Bussel's [31] graph based on the 'reliability' levels of *early stage* technology offshore wind turbines and has been adapted by extrapolation to account for lower levels of 'access' which weren't shown in the original graph. The '% access' level of 34% at M4 equates to an 'availability' of approximately 60% and at Leixoes, 68% and 90% respectively.

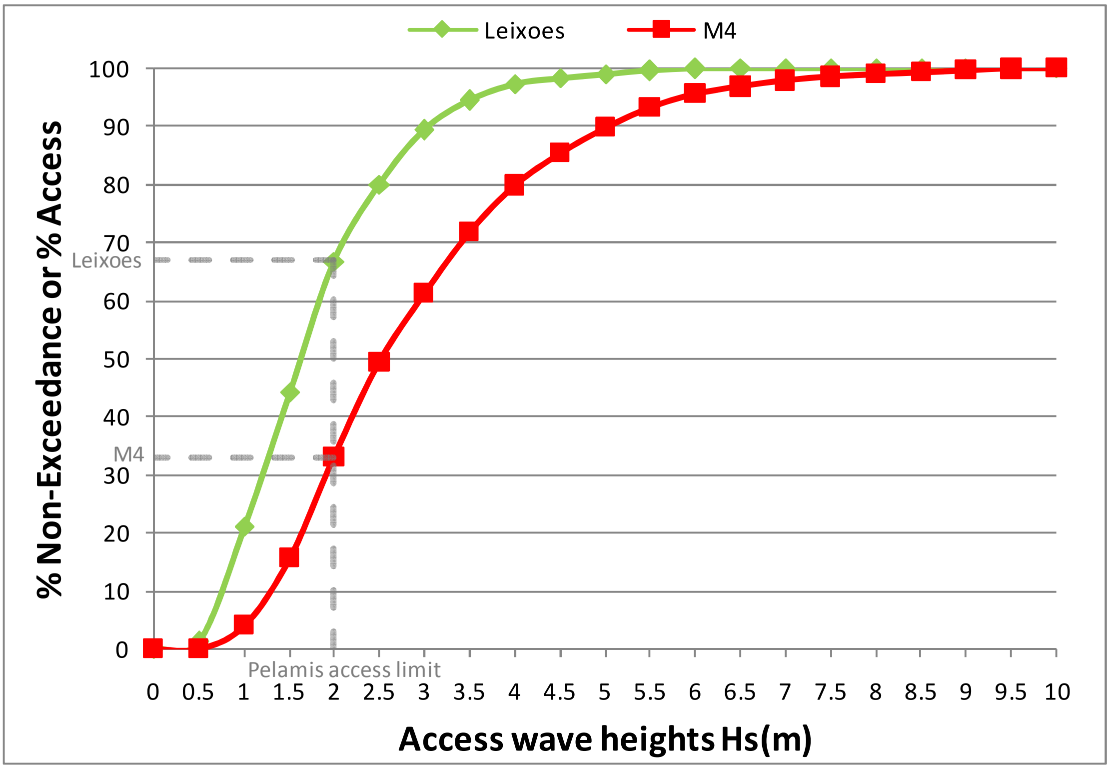

Figure 3 'Non-Exceedance' or 'Access' graph for M4 and Leixoes during 2007 showing the percentage of the year that the wave heights are below a certain level. Vertical line at 2.0m (Pelamis O/M access limit) shows wave height below limit for 34% of the year at M4 and 68% at Leixoes.

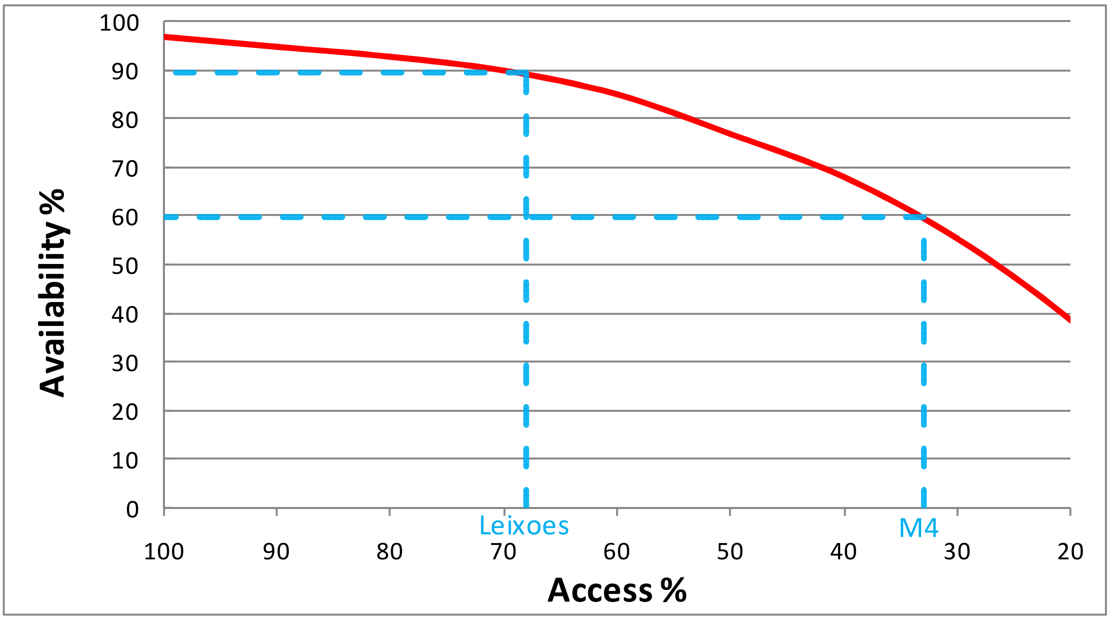

Figure 4 Availability -v- access levels, adapted from [31] based on reliability levels of early offshore wind turbines. Vertical lines show availability levels for M4 (34% 'access') and Leixoes (68% ' access').

4.3.1 Total annual energy output due to availability

The total annual energy output (TAEO) accounting for 'availability' is calculated according to Equation 3:

Equation 3 $TAEO = AEO * \%$

Where AEO is the Annual Energy Output and % is the 'availability' percentage.

4.4 Financial inputs

Annual cash flow (ACF) is the sum of the revenue in, TIC and OPEX (operational expenditure). This is summarised in Equation 4:

Equation 4 $ACF = -TIC - OPEX + revenue \ \ (FIT)$

Where OPEX includes O/M, insurance, utility charges and rent.

4.4.1 Total Initial Costs (TIC) or Capital Expenditure (CAPEX)

The IC_{wec} of the Pelamis chosen for this report was €1,600,000[7] obtained from the 2004 EPRI report in California [5]. The figure included costs for both the steel sections and all the internal components. For the purposes of this case study, 2011 cost for the Pelamis were based on a multiple of 2004 costs using the price of steel as the multiplying factor (Table 4). Dalton et al. [7] showed that the price of steel tripled from 2004 to 2008 and then dropped to double figures after 2009. Although it has slightly risen again a factor of two was used for 2011 initial costs.

		2004	**2011**
1 MW farm	IC_{wec}	$2100/kW	$4300/kW
	TIC	$4000/kW	$8000/kW
75 MW farm	IC_{wec}	$1250/kW	$2500/kW
	TIC	$2300/kW	$4600/kW

Table 4: The initial cost of WEC (IC_{wec}) and the total project initial cost (TIC), for a 1 MW project and 75 MW project for 2004 and 2011.

[7] WEC $1,565,000 + steel sections $850,000. US currency conversion to Euro was 1.50 (at June 2011).

The remainder of other costs were calculated as a percentage of the IC_{wec} (Table 5), and were based on costs by Dalton et al. [7]. This method allowed for simplified cost and sensitivity analysis.

WEC parameter	**% of IC_{wec}**
Mooring	10%
Cabling	10%
Replacement costs	90%
Spare parts	2%
Sitting and permits	2%
GHG investigations	0.05%
Decommissioning fees	5%
Grid connection	5%
Management fees	10% of total TIC

Table 5: Costs of WEC infrastructure, calculated as a percentage of the ICwec, based on Previsic [5].

A simplistic cable costs estimation of 10% of the IC_{wec} was used which equals €18.7m for 75MW. Preliminary simulations using NAVITAS of detailed cable costs have indicated that cable costs converge to 10% for large projects. Higher cable costs can be expected for smaller *early stage* projects as reflected by O'Sullivan et al [38] who estimated the offshore electrical equipment for a 20MW wave farm at the Belmullet site to be €10.5m.

Figure 5 provides a breakdown of the initial costs in percentage of the TIC, which were the same at both locations. The IC_{wec} totals 54% of the TIC in this study.

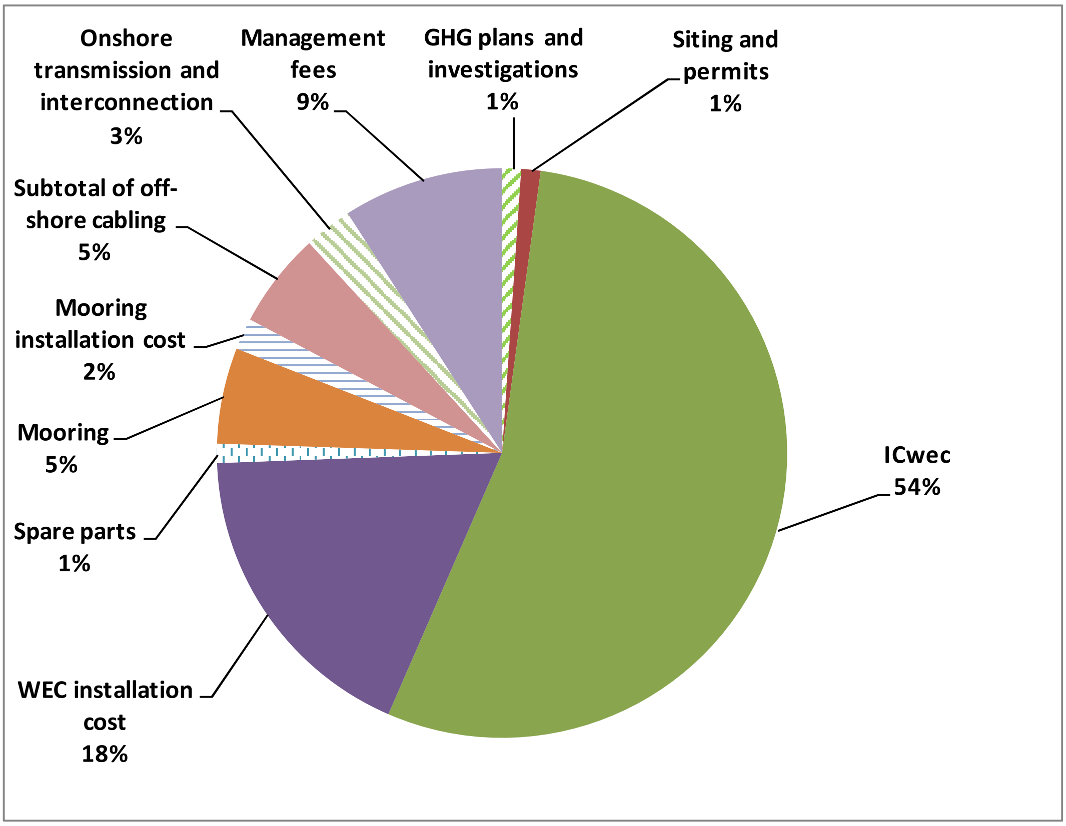

Figure 5: Percentage breakdown of TIC.

The project lifespan as 15 years, which was determined by the length of the FIT tariff currently available by the Irish government (discussed in a later section).

4.4.1.1 Discount factor (DF)

The discount factor (DF) translates expected financial benefits or costs in any given future year into present value terms. The total nominal profit is adjusted for cash depreciation by multiplying the total nominal profit by a discount factor.
DF is calculated using the discount rate, and is calculated by Equation 5.

Equation 5 $$DF = \frac{1}{(1+DR)^n}$$

The discount rate (DR) is an interest rate commensurate with perceived risk used to convert future payments or receipts (within a project lifetime) to present value. By defining the discount rate in this way, *inflation is factored out of the economic analysis* during the project lifetime. All costs therefore become *real costs*, meaning that they are in defined in terms of constant Euros. The assumption is that the rate of inflation is the same for all costs. For this project, wave farm modelled of 75MW is deemed fully commercial and low risk with a corresponding discount rate of 6%.

4.4.1.2 Feed-in tariff (FIT)

Feed-in tariff (FIT) refers to the regulatory, minimum guaranteed price per kWh that an electricity utility has to pay to a private, independent producer of renewable power fed into the grid [39]. It is defined in this report as the full price per kWh received by an independent producer of renewable energy including the premium above or additional to the market price, but excluding tax rebates or other production subsidies paid by the government. Grid sales are a credit, and are added to other negative cost values for each year. The sales are the product of the following two variables:

- The total energy produced each year, referred to as the total annual energy output (TAEO).
- The electricity tariff rate from the utility company.

The tariff rate used for this case study was €0.30/kWh recommended by Dalton et al [7] which was estimated in that paper to produce a positive financial return and IRR for an Irish wave farm. Feed in tariffs may need to be higher however, as recommended by Dalton [40] which recommends a FIT of €0.35/kWh when staggered installation over a 10 year period is taken into account.

4.4.1.3 Discount factor for multiple devices

The cost of purchasing multiple devices is cheaper than buying a singular device, due to discounts provided by manufacturers to encourage multiple purchases. The discount is based on a cumulative factorial reduction in price. The cumulative total of *n* number of devices is the sum of the discounted costs, derived in Equation 6.

Equation 6 $$Total\ \ ICwec = \sum_{1}^{n} P_n *\ ICwec_n$$

P is the percent reduction used in IC costing for WEC, derived in Equation 7:

Equation 7 $$P = N^{\ln(bdf)/\ln(2)}$$

Where N is the number of WEC components and 'bdf' is the bulk discount factor.

4.4.2 Operational Expenditure (OPEX)

The OPEX inputs for the case study were based on average inputs derived from the literature review section.

4.4.2.1 Operation and maintenance (O/M)

O/M in this case study is calculated by the following Equation 8:

Equation 8: $O/M_{wec} = (IC + instal)_{wec} * O/M\%_{wec}$

Where O/M_{wec} refers to O/M of the WEC, $(IC\text{+}install)_{wec}$ refers to cost of the device plus its installation costs and $O/M\%_{wec}$ refers to the percentage value chosen for O?M of the WEC.

Four rates for O/M (1%, 3%, 5%, 10%[8]) are examined to assess their impact on (NPV) of a project. Total annual O/M in this case study is derived from the sum of O/M of the following 3 major project components: WEC, Cable and Mooring (Equation 9). The majority of the modelling in this report applies a uniform % for all three component categories. However, there is one simulation which inspects varying percentages.

Equation 9 $Total\ \ O/M = sum\ \ (O/M_{wec} + O/M_{mooring} + O/M_{cable})$

Where O/M_{wec} refers to O/M of the WEC, $O/M_{mooring}$ refers to O/M of the mooring and O/M_{cable} refers to O/M of the cable.

4.4.2.2 Overhaul

For some case study simulations, the WEC devices are taken out of the water and receive a general overhaul (or refit) every 4 years. The cost of the overhaul per device was taken as 10% of IC based on an estimate by [5]. Annual overhaul costs are based on the average overhaul cost averaged over the entire project life, in Equation 10:

Equation 10 $$AOC = \frac{\sum(total\ \ overhaul\ \ \cos ts)}{project\ \ years}$$

Where AOC is the annual overhaul cost.

4.4.2.3 Replacement

For some case study simulations, the WEC devices are completely replaced every 10 years. The cost of replacement per device was taken as 90% of IC_{wec}. Annual replacement costs are based on the sum of the replacement cost averaged over the entire project life, in Equation 11:

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[8] Example of nomenclature in results section: 1%O/M = operation and maintenance calculated as 1% of initial cost of the WEC (IC) + installation.

Equation 11 $ARC = \frac{\sum(total\ \ replacement\ \ costs)}{project\ \ years}$

Where ARC is the annual replacement cost.

An example of a schedule of overhaul and replacement expenses for WEC, cable and mooring is presented in Table 6.

			Replace	Overhaul	Replace	Overhaul	Replace	Overhaul
Year	Discount	Total Initial cost	Cost	Cost	Cost	Cost	Cost	Cost
	Factor		WEC	WEC	Mooring	Mooring	Cable	Cable
0	1.0000	-341,084,780						
1	0.9581							
2	0.9180							
3	0.8796							
4	0.8428			-18,721,409		-1,872,141		-1,872,141
5	0.8075							
6	0.7737							
7	0.7413							
8	0.7103			-18,721,409		-1,872,141		-1,872,141
9	0.6805							
10	0.6521		-168,492,677		-16,849,268		-16,849,268	
11	0.6248							
12	0.5986			-18,721,409		-1,872,141		-1,872,141
13	0.5736							
14	0.5495							
15	0.5265							

Table 6: An example schedule of overhaul every 4 years and replacement every 10 years, for WEC, cable and moorings, for 75MW project at €0.30/kWh, 1%Insurance and 3%O/M. (for simplicity, overhaul still takes place in year 12 despite the fact that replacement occurred in year 10).

4.4.2.4 Insurance

For this assessment, 4 rates for insurance (1%, 3%, 5%, 10%[9]) are examined to assess their impact on net present value of a project. The rates are multiplied with the TIC according to Equation 12:

Equation 12 $Insurance = TIC * Insurance\ \ \%$

Where Insurance% is the percentage rate chosen for insurance.

[9] Example of nomenclature in results section: 1%Insurance = insurance calculated as 1% of total initial cost.

5 Scatter plot of hours

5.1 *Ireland M4*

Table 7 presents the scatter plot of hours for the M4 buoy located off the West coast of Ireland, for 2007. The method used in this paper 'floors' the Hs and Tz values when binning the hours. The highest frequency of hours lies within the periods of 5-7 seconds and wave heights of between 1- 2.5m.

Hs(m)	Tz(s)													
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
0.5	0	54	136	25	0	2	0	2	2	0	0	0	0	0
1	0	157	437	199	82	22	0	0	0	0	0	0	0	0
1.5	0	32	561	453	251	96	28	4	0	0	0	0	0	0
2	0	0	274	636	352	209	57	9	0	0	0	0	0	1
2.5	0	0	42	400	380	176	77	13	0	0	0	0	0	0
3	0	0	1	196	441	215	77	16	7	0	0	0	0	0
3.5	0	0	0	37	338	248	83	22	5	5	1	0	0	0
4	0	0	0	4	143	228	119	25	5	4	1	0	0	0
4.5	0	0	0	0	59	207	113	18	3	8	3	0	0	0
5	0	0	0	0	5	149	116	31	4	0	1	0	0	0
5.5	0	0	0	0	0	55	120	37	3	0	0	0	1	0
6	0	0	0	0	0	17	72	35	1	5	0	0	0	0
6.5	0	0	0	0	0	6	29	41	9	4	1	0	0	0
7	0	0	0	0	0	0	16	36	15	2	0	0	0	0
7.5	0	0	0	0	0	0	6	31	14	4	0	0	0	0
8	0	0	0	0	0	0	1	15	9	6	0	0	0	0
8.5	0	0	0	0	0	0	0	4	13	4	0	0	0	0
9	0	0	0	0	0	0	0	6	14	1	2	0	0	0
9.5	0	0	0	0	0	0	0	2	9	1	0	0	0	0
10	0	0	0	0	0	0	0	0	2	0	1	0	0	0
10.5	0	0	0	0	0	0	0	0	0	1	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7: Scatter plot of hours for M4 buoy off the west coast of Ireland, 2007. (made available from HMRC, Ireland www.ucc.ie/research/hmrc)

5.2 *Portugal Leixoes*

Table 8 presents the scatter plot of hours for the Leixoes buoy located off the Atlantic coast of Portugal, for 2007. The highest frequency of hours lies within the periods of 5-7 seconds and wave heights of between 0.5- 1.5m.

Hs(m)	Tz(s) 3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	9	32	51	9	1	0	0	0	0	0	0	0	0	0
0.5	58	412	585	396	207	64	6	0	0	0	0	0	0	0
1	4	336	627	438	268	173	164	24	2	0	0	0	0	0
1.5	0	118	583	485	296	235	171	72	16	0	0	0	0	0
2	0	0	189	331	224	211	99	61	44	0	0	0	0	0
2.5	0	0	20	224	174	156	143	75	25	4	0	0	0	0
3	0	0	0	58	108	103	71	85	15	6	0	0	0	0
3.5	0	0	0	4	45	63	50	66	30	2	0	0	0	0
4	0	0	0	0	12	23	28	8	12	0	0	0	0	0
4.5	0	0	0	0	1	8	28	14	5	4	0	0	0	0
5	0	0	0	0	0	9	13	22	2	3	0	0	0	0
5.5	0	0	0	0	0	0	3	9	2	3	7	0	0	0
6	0	0	0	0	0	0	0	0	2	6	2	1	0	0
6.5	0	0	0	0	0	0	0	0	1	3	1	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8 Scatter plot of hours for Leixoes buoy off the Atlantic coast of Portugal 2007 (made available from Instituto Hidrográfico, Lisbon www.hidrografico.pt).

The average power of the waves in 2007 was 53.6kW/m at the M4 location and 19.9kW/m at Leixoes. Figure 6 presents the average hourly power output from a Pelamis device at M4 and Leixoes for each month in 2007, showing a large variation between winter and summer outputs, in particular for M4.

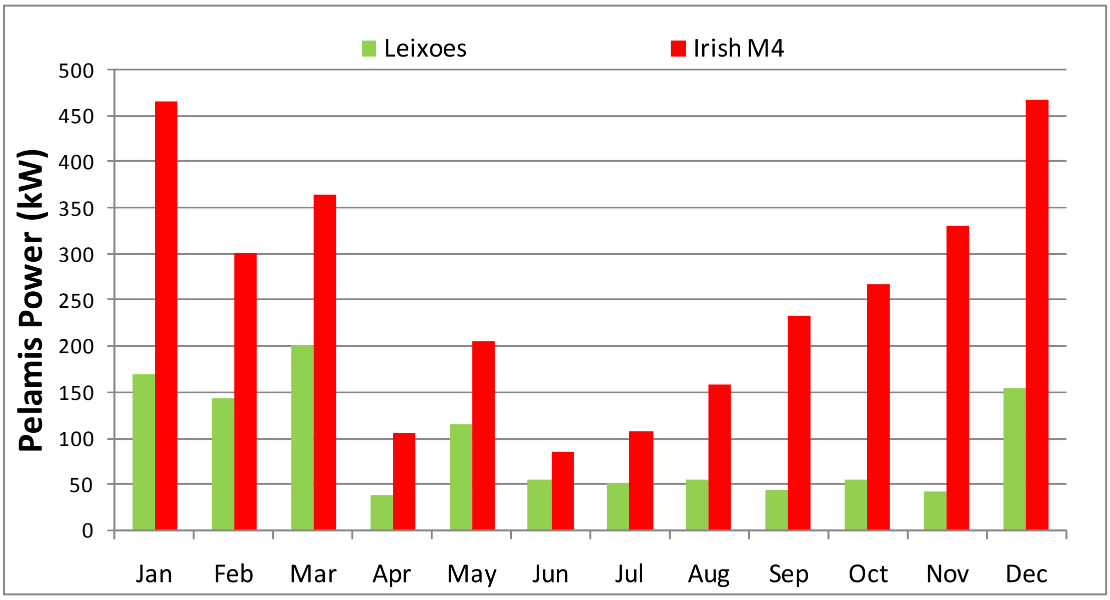

Figure 6: Average hourly power output from the Pelamis (kWh) for each month in 2007 at M4 and Leixoes buoys.

6 Results

6.1 €/MWh and % of OPEX

Figure 7 displays the breakup of the total OPEX costs over the 15 project. Figure 7A presents the proportion of OPEX costs without overhaul and replacement, where O/M and insurance account for all of OPEX, at 72% and 28% respectively. Figure 7B presents OPEX with overhaul and replacement included. The sum of overhaul and replacement costs comprises 60% of total OPEX, averaged out over the 15 year project. O/M and insurance each account for 29% and 11% respectively. O/M costs are within the average % OPEX quoted in the literature review (Table 1) when overhaul and maintenance are included.

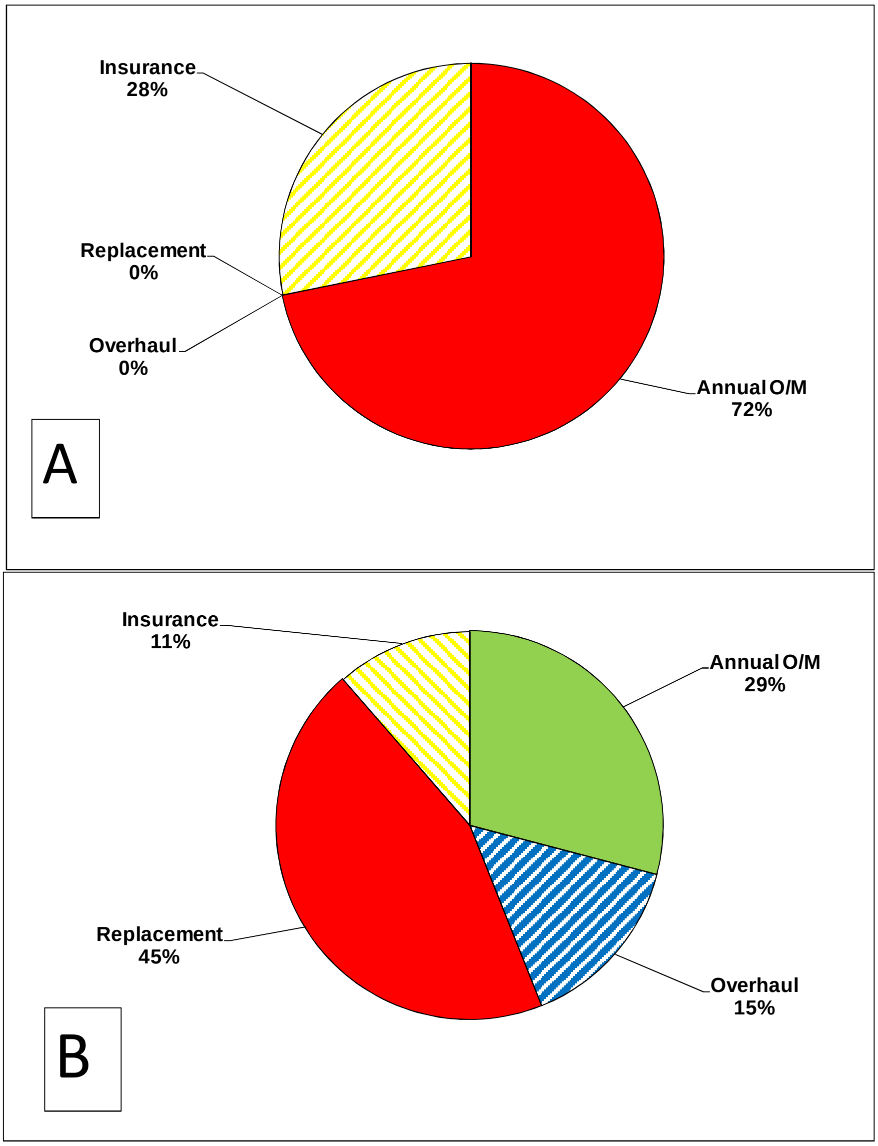

Figure 7 Break up of OPEX expenditures (Same for both sites), A − no overhaul and replacement B – overhaul (10% of IC_{wec}) every 4 years, replacement (90% of IC_{wec}) every 10years. O/M was simulated at 3% Insurance simulated at 1%O/M.

Table 9 presents the breakdown of the expenditure results from a €/MWh perspective for both locations, 3%O/M and 1%Insurance. O/M costs of €52/MWh for M4 and €129/MWh for Leixoes were above the average quoted in the literature review for wave energy in Table 1. The high O/M results indicate that O/M costs calculated at 3% of TIC maybe too high for a project.

1%Insurance resulted in insurance costs of €20/MWh at M4 and €51/MWh in Portugal, or 11% of OPEX, which is similar to that quoted by EWEA and IWEA of 13-14% of OPEX respectively [15, 24]. If insurance costs of 2%Insurance are modelled, as quoted by Carbon Trust and EPRI [5, 14], insurance costs equal 20% of total OPEX (in brackets in Table 9) and €41/MWh at M4 and €101/MWh for Portugal.

	% of total OPEX	M4 €/MWh	Leixoes €/MWh
Annual O/M	29%	€52	€129
Overhaul	15%	€26	€66
Replacement	45%	€79	€198
Insurance[a]	11% ([a]20%)	€20 ([a]€41)	€51 ([a]€101)
Total	100%	€178([a]€198)	€443([a]€494)

Table 9: Results for the break down on expenditure costs for a 75MW wave farm at both M4 and Leixoes, using O/M at 3% of IC and insurance at 1% of IC. [a]results for insurance modelled at 2% of IC are in brackets.

6.2 NPV and IRR sensitivity analysis

6.2.1 Varying O/M, constant insurance

Figure 8 displays the NPV at the end of the 15 year project for a 75MW wave farm at M4 and Leixoes at a FIT of €0.30/kWh, 1%Insurance and ‘availability’ at 60% and 90% at M4 and Leixoes respectively. Annual O/M expenses were simulated at 1%, 3%, 5% and 10%. Results indicate that none of the simulations resulted in a positive NPV for Leixoes despite its 90% ‘availability’ figure. Positive NPV figures were achieved at M4 but only at 3%O/M or less. No overhaul or replacement costs were considered in this simulation. None of the scenarios in Figure 8 resulted in an IRR of 10% or above, with the highest IRR of 8.2% achieved at M4 for 1%Insurance and 1%O/M.

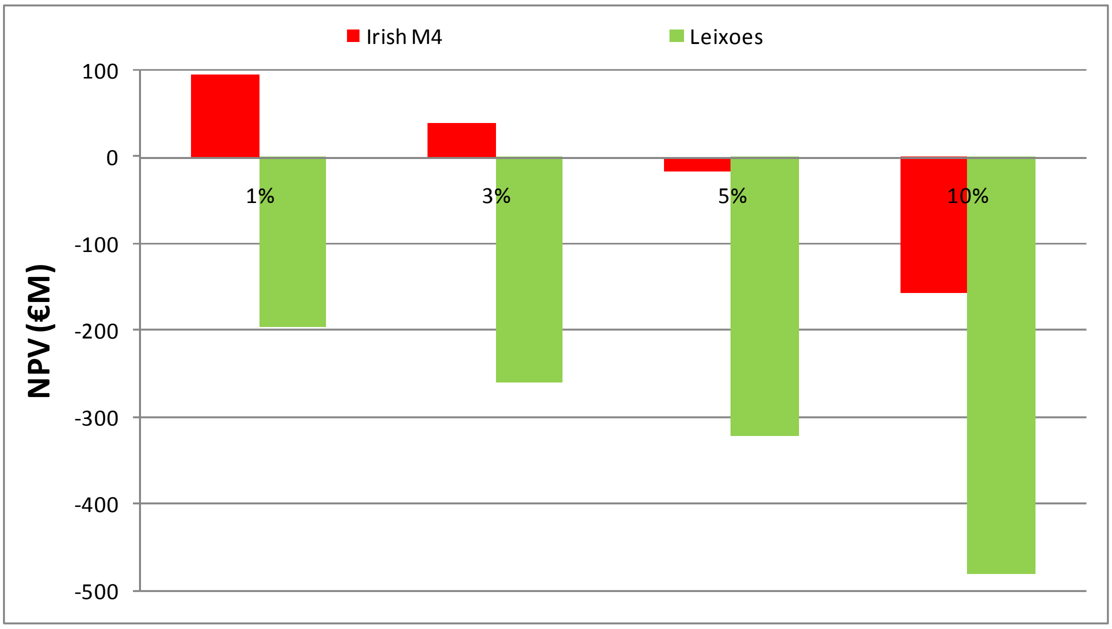

Figure 8 NPV (€M) for 75MW project at M4 and Leixoes for varying levels of annual O/M expenses (1%, 3%, 5%, 10%). (Insurance fixed at 1%, FIT €0.3/kWh, no overhaul and replacement)

6.2.2 Varying insurance, constant O/M

The impact of varying levels of annual insurance costs is assessed in Figure 9. In this simulation O/M expenses were fixed at 3%O/M with the insurance levels at 1%, 3%, 5% and 10% of TIC. All other variables remain the same. Simulations for Portugal resulted in negative NPV. At M4, a positive NPV was achieved only if the insurance rates were at 1%Insurance.

Figure 9 NPV (€M) at the end of year 15 of the 75MW project at M4 and Leixoes for varying levels of Insurance (1%, 3%, 5%, 10%). (O/M fixed at 3%, FIT €0.3/kWh, no overhaul and replacement)

6.2.3 Varying farm size at Ireland M4

Given that the only positive NPV results were achieved at M4, the remaining analysis is performed on M4 only and at an insurance rate of 1%Insurance. Figure 10 displays NPV and IRR results at M4 for various combinations of project sizes and O/M costs, based on a FIT of €0.30/kWh and no overhaul and replacement costs. The only scenarios which produced a positive NPV for a 75MW farm were when O/M costs at 3% or less. However as the wave farm size increased to very large farms up to 200 or 500MW, the economies of scale resulted in increasing IRR results as well as positive NPV for O/M cost up to 5%O/M.

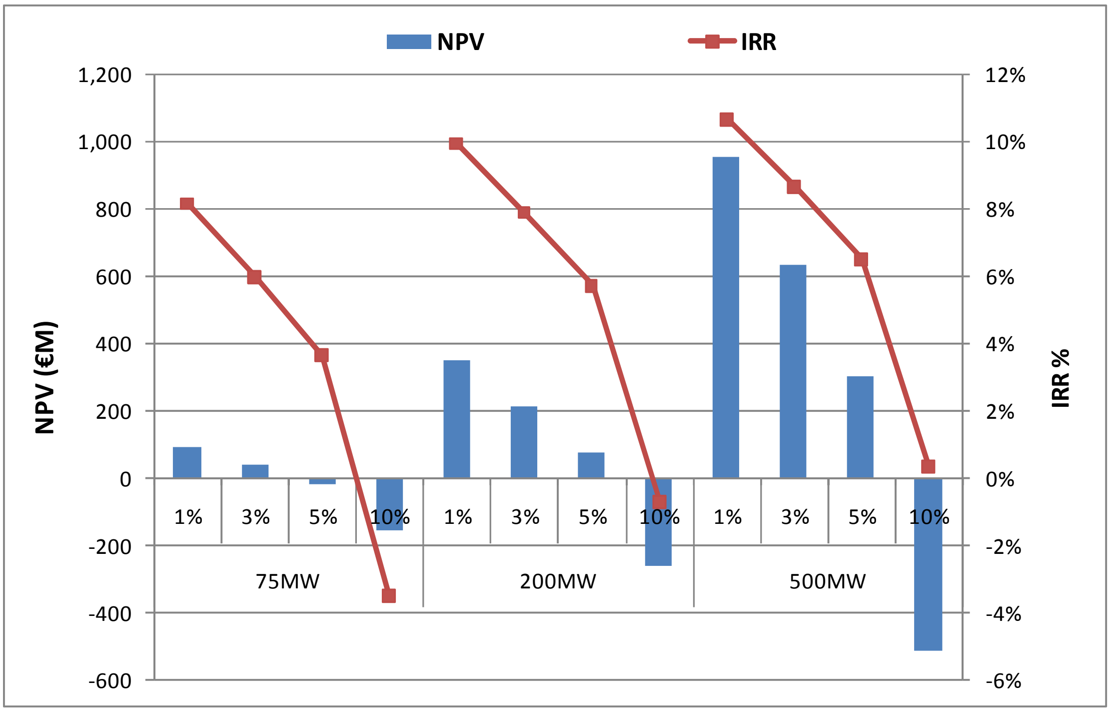

Figure 10 M4 NPV and IRR for varying O/M and different farm sizes. (Insurance fixed at 1%TIC, €0.3/kWh, 60% 'availability', no overhaul and replacement)

6.2.4 Overhaul and Replacement

The resultant cash flows for modelling replacement at 10 years, and overhaul planned every 4 years are shown in Figure 11 for M4. Results indicate that the 3 schedules of overhaul have little impact on the cumulative cash flows over the 15 year period. However, the replacement of the components at year 10 has sufficient impact to move all O/M scenarios into the negative NPV. The impact was larger than might be expected, considering that the actual cost of replacement would be heavily discounted by the relevant discount factor appropriate to year 10.

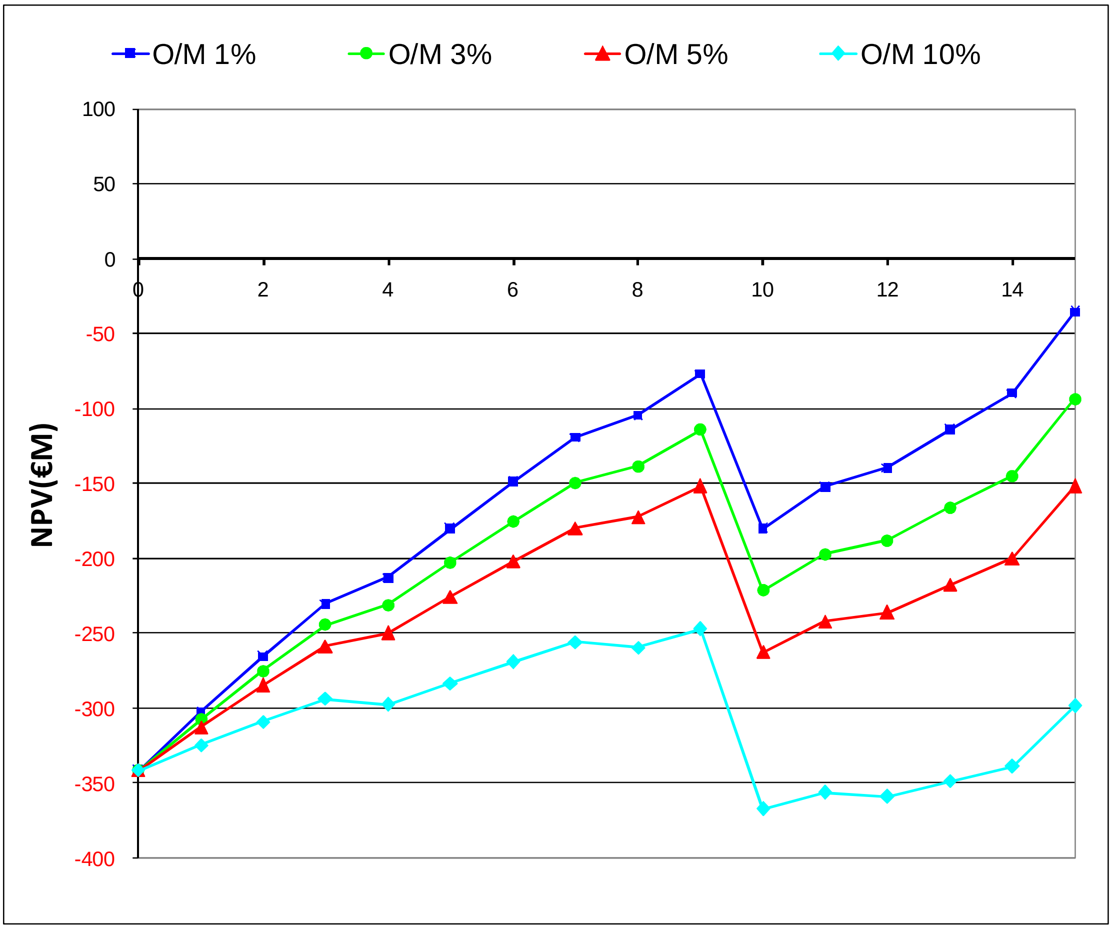

Figure 11 M4 cumulative cashflows for a range of O/M expenses with overhaul every 4 years and replacement after 10 years. (Insurance fixed 1%TIC, 60% 'availability')

6.2.5 WEC Cable and Mooring O/M

Figure 12 presents cash flow analysis inspecting the scenario of splitting O/M expenses into their subcomponents for WEC and cable (for the sake of clarity in the graph, mooring cost element was not presented). O/M increase from 1% to 5% for the WEC component had more impact on NPV than a similar increase for cable maintenance, as expected due to their difference in IC.

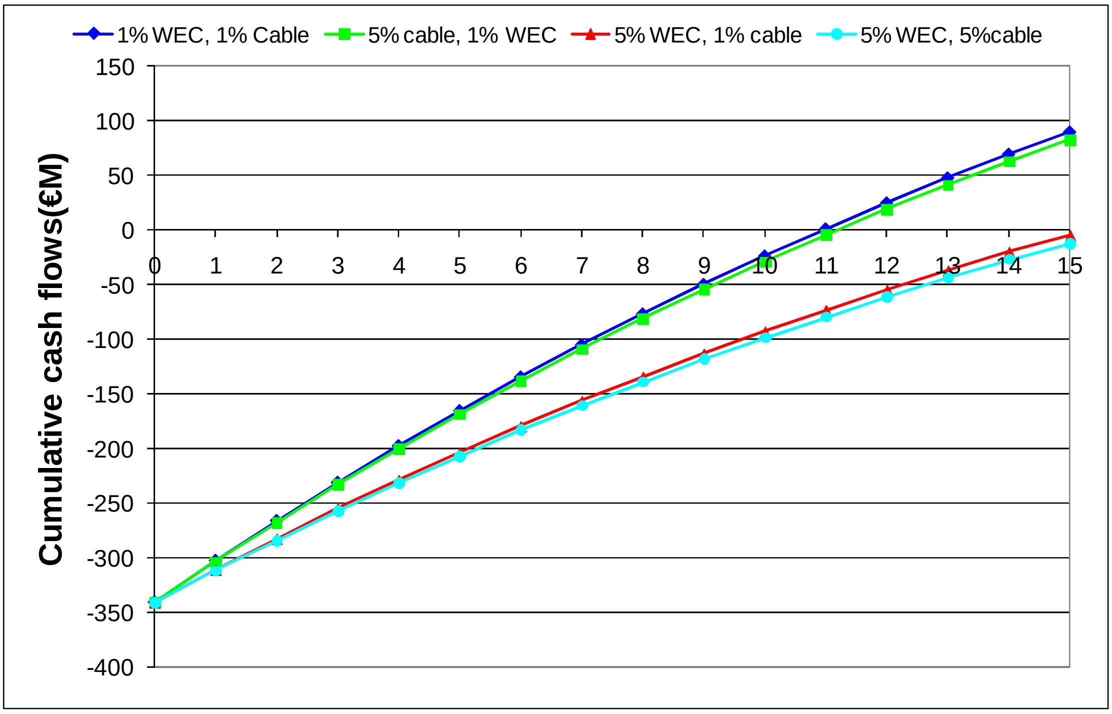

Figure 12 M4 cumulative cashflow for varying levels of O/M for either WEC and or cable (mooring fixed at 3%, insurance 1%, no overhaul and replacement, 75MW FIT €0.3/kWh)

6.3 Tariff or availability required for 10% IRR

This section examines what FIT would be required to produce an IRR of 10% at both M4 and Leixoes. Results indicate that at M4, with 1%Insurance and 3%O/M, the required FIT would need to be €0.33/kWh. Using the same criteria in Portugal, a FIT of €0.60/kWh would be required to produce a zero NPV by the end of the project, and €0.82/kWh to produce a 10% IRR.

The 60% ‘availability’ level of a wave farm at M4 is as a result of the low levels of ‘access’ (34%) and the potentially lower reliability levels of a technology at an *early stage* of development. In order to achieve ‘availability’ levels similar to those that are currently achieved in the mature offshore wind industry (90%+), the levels of access would need to be improved, together with the devices having a very high level of reliability. If these *mature stage* reliability levels were used in the modelling, simulations reveal that for an ‘availability’ level of 90% at M4, with 1%Insurance and 3%O/M expenses, the current proposed Irish FIT of €0.22/kWh would result in an IRR of 10%.

7 Summary

‘Access’ and ‘availability’ factors for *early stage* wave energy technology had significant impact on the total energy output available, resulting in M4 handicapped with a 40% drop in AEO and Leixoes a 10% drop in AEO. The reduced energy outputs impacted on financial returns.

Case study simulation results for O/M rates in €/MWh were above the average reported for wave energy and offshore wind in the literature review; O/M rates of €52/MWh at M4 & €129/MWh at Leixoes and insurance rates of €20/MWh M4 & €51/MWh at Leixoes. The total cost for all OPEX was €72/MWh for M4 and €180/MWh for Leixoes (€178/MWh and €443/MWh respectively when overhaul and replacement were included).

No scenario at Leixoes resulted in a positive cashflow in this case study, even with the most optimistic scenario of low O/M and insurance costs of 1%TIC, with no overhaul and replacement. M4 achieved positive cashflows when O/M or insurance were at 1%TIC, with the other factor no higher than 3%TIC. None of the scenarios at M4 however resulted in an IRR of 10% with the highest IRR being 8.2% for insurance and O/M at 1%TIC, with no overhaul and replacement. Larger wave farms produced higher NPV and IRR due to economies of scale, and consequently enabled higher O/M and insurance costs while still maintaining a positive NPV and IRR. In order to produce a 10% IRR in an M4 modelled scenario of 75MW and 1%Insurance and 3%O/M, a FIT of €0.33/kWh would be required. However, if an availability rate for *mature stage* technologies is used for modelling, the current FIT in Ireland of €0.22/kWh would be sufficient to produce an IRR of 10%.

The O/M of the WEC was the most significant contributor to overall O/M (in comparison to cable and mooring) as expected due to the higher IC of that component. Variation in insurance costs is the other major factor which has significant impact on NPV. Overhaul expenses did not have a significant impact on modelled scenarios, whereas replacement cost in the 10th year accounted for almost half of the total OPEX.

8 Discussion and conclusion

Access and resultant availability factors had a significant impact on this case study by reducing energy output and correspondingly financial returns. Furthermore, the technology maturity level designated for a project also impacted on availability factors and consequently energy output and NPV. Increased O/M procedures and costs would be expected to occur in locations with adverse access and availability. This aspect was assessed under the sensitivity analysis for various O/M scenarios. Direct O/M consequences due to reduced availability would be the topic of a future research.

The use of the €/MWh metric, when specifying O/M and OPEX, can be easily misinterpreted if not correctly defined as it is location specific. The metric has similar limitations as the cost of electricity (COE) metric, which was discussed in a paper by Dalton et al [7].

Feed-in-tariffs will need to be tailored to the location in question as well as the device technology maturity level, with case study simulations indicating that high FIT will be required to support early stage WEC projects. Case study profits were very sensitive to annual OPEX, especially if overhaul and replacement costs were accounted for. Results indicate that device designers will need to choose whether to opt for longer lasting more expensive devices which require lower annual maintenance costs, or cheaper devices with shorter device lifetimes requiring overhaul mechanisms that enable easy and cheap retrieval from ocean site to maintenance dock. More detailed research is required to determine exact insurance and O/M costs as well specifics of device service times and device lifespan, as well as more detailed weather windows, before more OPEX costs estimates for wave energy projects can be confidently assessed.

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