Challenges in the Grid Connection of Wave Energy Devices

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Abstract

In considering the grid connection of ocean energy devices, and in particular, the connection of large offshore arrays, there are a number of technical and non-technical challenges that need to addressed by wave energy device developers. As device developers approach pre-commercial operation, grid connection factors will become increasingly significant in both technical and financial terms. In this paper some generally applicable technical and non-technical challenges are examined. A grid connection costing case study in the Irish context is performed as a practical indicator of these issues.

Keywords: wave energy, grid connection, cost study, generators.

Nomenclature

UPS	=	Uninterruptible Power Supply
WEC	=	Wave Energy Converter
CB	=	Circuit Breaker
CT	=	Current Transducer
VT	=	Voltage Transducer
SCADA	=	Supervisory Control and Data Acquisition
SG	=	Synchronous Generator
DFIG	=	Doubly Fed Induction Generator
PMG	=	Permanent Magnet Generator
SCIG	=	Squirrel Cage Induction Generator
LCTA	=	Least Cost Technically Acceptable
PCC	=	Point of Common Coupling
THVD	=	Total Harmonic Voltage Distortion

1 Introduction

The integration of ocean wave energy converters into a national electricity grid represents a significantly different challenge to the integration of most other renewable technologies such as on-shore wind, solar photovoltaic, biomass, hydroelectricity etc. Apart from the fundamental distinctions in terms of the particularities of the different energy resources themselves, there exists a divide in terms of scalability and economics of scale. Most of the aforementioned technologies readily lend themselves to local small-scale and even domestic embedded generation. For instance, the development of on-shore wind technology has generally moved gradually from such small scale embedded generation plant to the large wind farms in operation today, and is now steadily moving towards the deployment of very large scale offshore wind generation. This development curve has been relatively continuous (in terms of gradual increase in typical power output) and by means of this approach, much valuable experience in the grid integration of wind power has been steadily gained, both from the viewpoint of developers and grid operators.

Clearly, grid integrated WECs do not lend themselves to such a development path. The actual development of the devices themselves should followed the recommended scaling protocol [1], however, scaled WECs are usually not grid connected due to the cost associated with the grid connection itself, which would render redundant the entire philosophy of the wave energy development protocol, although there is perhaps an argument for the deployment of temporary grid connections for scaled WECs that are tested at sea, above a certain power level.

At the prototype stage, the grid connection of full scale or pre-commercial scale devices is likely to be funded by government agencies, at predefined test sites, as is the case in Ireland, the UK, Portugal and Spain. In this regard, developers will remain relatively shielded from the technical and cost implications of grid connection However, once wave energy developers move to commercial operation, they will immediately be faced with this very significant challenge.

Some of the more important aspects of this challenge are outlined in this paper. These are subdivided into grid-side challenges, and generator-side challenges, where the latter represent the implications on generator selection and design that are a direct result of grid connection requirements. A costing case study is carried out to illustrate the effect on development costs of these factors. It is anticipated that, initially, wave power device arrays will be connected to the distribution network. This effectively limits rated power outputs to 10-20MW for a wave farm, and it is on such a size of system that the case study is performed. Larger farms will require direct connection to the transmission grid.

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2 Grid-Side Challenges

It may be considered that obstacles or challenges related to the electricity grid infrastructure are not the responsibility of ocean energy device developers. This is however only partially true. While it is incumbent on national grid operators to strategically develop their infrastructure, and to plan for the likely location of future large-scale generation, they are under no specific obligation to do so. Furthermore, depending on the grid connection charging regime in operation within the jurisdiction, the device developer may have to cover a significant proportion of the costs associated with any required infrastructural upgrades to the electricity network resulting from the connection of the new generation plant.

Charging Regimes

The two main connection charge approaches are generally known as 'deep' charging and 'shallow' charging. Under a shallow charging regime, the developer is required to pay for the cost of all engineering works up to the point of the grid connection itself. This charge usually includes the connection assets, i.e. substation and associated equipment and may include any extensions required to the grid, between the existing network and the connection point. In cases where the grid operator covers the costs of any network extensions, the regime is termed 'super shallow'.

Within a deep charging regime, extra costs associated with upgrades and reinforcement of the existing network due to the connection of the extra generation must also be covered by the developer. Some countries offer a 'semi-shallow' regime whereby the developer pays only a proportion of the network upgrade costs, based on the proportion of the power produced by the developer to the total power flow through the elements that must be upgraded.

An illustration of the connection charge concepts is provided in Figure 1, where the connection of a new wave generator to the grid is depicted. A shallow charging regime would mean the developer must pay for the items marked in red, to the left of the shore connection point, and some or all of the items marked in blue up to the point of connection to the existing grid. For a deep charging regime, any upgrade required to the existing network transformers, breakers, and power lines, due to the presence of the new generator would have to be covered by the developer.

Deep charging is marginally prevalent within the EU [2], despite the stated preference of EU policy makers for shallow charging regimes for the encouragement of renewable energy generation. However, this situation does appear to be changing with more countries recently migrating to shallow charging regimes. Deep charging is usually coupled with a significant degree of negotiation between the developer and the network operator, in order to determine the exact costs of connection. This negotiation process has been seen as putting the network operator in a position of strength, and along with a lack of transparency, has put developers at a significant disadvantage.

Use of System Charges

Apart from specific connection charges many network operators apply Use of System (UoS) charges [2, 3] to generators for the bulk transmission of the generated energy to the load centres. Often, the cost of system upgrades and reinforcements are recouped via these charges, particularly in shallow charging regimes. Recouping the costs in this manner shares them between all generators. The UoS charges can be location dependent if there are particularly high reinforcement costs or transmission losses associated with a given region. UoS charging policy varies widely across the EU, with a significant proportion of countries that do not apply them at all. In these cases, the costs of reinforcing and maintaining the electricity network are borne by the electricity end user.

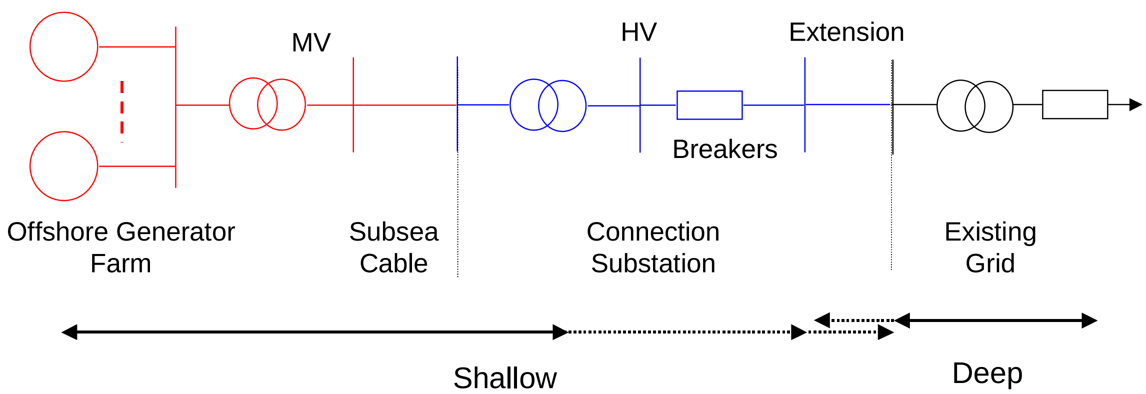

Figure 1: Illustration of connection charging setup

Charges in the Irish context

The connection charging regime in Ireland is mixed. Connection charges to the transmission system are specifically outlined as shallow charges, with the generator being liable only for 'connection assets', and not for 'system assets' [4]. Connection assets are defined as *"those assets, which are installed to enable* *the transfer of the Maximum Export Capacity (MEC) or the Maximum Import Capacity (MIC) of the User's facility, to or from, as appropriate, the Transmission System for the term of the Connection Agreement in accordance with the Grid Code and Transmission and Distribution System Security and Planning Standards and those assets which are installed as a result of the User's effect on fault current levels on the transmission system at the transmission node to which the User connects, but <u>does not include any assets installed at any location other than the transmission node to which the User connects</u>*" [4]. Charges are calculated based on the Least Cost Technically Acceptable (LCTA) method [4, 5], and reflect the cost of constructing, installing, and maintaining the connection assets. This method determines the cost based on the cheapest connection arrangement that would satisfy the appropriate grid code requirements. If the system operator decides to actually build the connection on an alternative route, the charge applied to the generator will remain at the LCTA level, unless the generator specifically requests a more costly alternative, and this request is granted. These charges do include any decommissioning costs associated with modification of the existing transmission network in order to incorporate the new generation equipment.

Connection charges to the Irish distribution network are handled in a similar fashion, although a charge is applied for those reinforcement works on the distribution network that are required to enable the generator to export maximum capacity [5]. This is essentially a deep connection charge for distribution network connections.

Transmission UoS charges in Ireland are location-linked, and are also based on maximum export capacity [3]. This situation is not favourable to ocean energy developers since the remote location of most ocean energy particularly off the north-west coast is likely to incur a significant location-based UoS charge. Likewise, charging on the basis of maximum capacity is unfavourable to renewable energy sources in general due to their low capacity factor when compared with traditional generation sources.

3 Generator-Side Challenges

The selection of a generator type for wave energy converters (WECs) is an issue that involves several tradeoffs. These include cost, environmental factors, generation efficiency, reliability, as well as grid connection suitability. For most WECs, with the exception of direct-drive linear motion devices, the generator will typically be a rotating electrical machine which is either directly grid-connected or connected through a power electronics converter. The vast majority of traditional fossil fuel based generation plant consists of grid-connected synchronous generators. In similar manner to other renewable energy technologies, however, this choice is not usually desirable. Typically, some level of generator speed variation is required in order to optimise power take-off and matching to the renewable source. Hence, power electronics frequency converters are typically employed either in the rotor circuit – in the case of doubly fed induction generators (DFIG) – or in the stator circuit, in which case the generator machine is typically a permanent magnet (PMG) or separately excited, synchronous generator (SG), or a squirrel cage induction generator (SCIG). The advantage of the DFIG configuration is that the rating of the power converter is usually limited to 25%-40% of the generator power rating, thus saving on cost and efficiency. The tradeoffs between the various generator options in terms of environmental considerations, energy efficiency, cost and reliability have been examined in [6]. In this paper, the influence of grid connection requirements on the generator choice is considered.

Distribution and Grid Code Requirements

The Distribution Code [7] is a scheme of regulations and requirements, both technical and non-technical, which is applicable to electricity generators whose equipment is connected to the distribution network. It is likely that in the short to medium term, the distribution network will be the likely point of connection for wave energy generators. As power levels and wave farm scale increases into the future, connection points will migrate to the transmission network. The Grid Code [8] will then become the appropriate regulatory documentation.

The Irish distribution network nominal voltage levels are defined as indicated in Table 1.

Low Voltage (LV)	400V
Medium Voltage (MV)	10kV 20kV
High Voltage (HV)	38kV 110kV

Table 1: Distribution Network nominal voltage levels.

The Distribution Code sets regulatory limits on the technical performance of generators connected to the network. These are outlined in the following sections, and their potential impact on the selection and design of an appropriate generator and associated power electronics (if required) and control system are discussed. The general Distribution Code requirements as well as those specific to wind turbine generators are taken into account, under the assumption that the requirements for wave energy generators will be somewhat similar to those that have been developed for wind energy. The Grid Code requirements are broadly similar to the Distribution Code requirements and in fact they overlap for the higher power connections.

Flicker

The flicker emission limits at the Point of Common Coupling (PCC) are set to the following values:

- Short Term Flicker Severity, P_{ST}=0.35
- Long Term Flicker Severity, P_{LT}=0.35

as defined by the flicker standard EN 61000-3-7 [9]. The flicker requirements are important in the context of the generator control system. Wave energy is by its nature pulsating, and while the pulsation frequencies tend to be significantly lower than those where flicker limits are most stringent, the amplitudes can be very large. Thus, care must be taken to ensure that the flicker emission limits are not breached. This has implications for the generator control system, as it may involve some power smoothing to reduce the pulsation amplitudes. Power smoothing generally involves some mechanical or electrical energy storage in the generator system. This imposes the requirement for some variable speed control capability and/or power electronics converters with electrical energy storage.

Voltage Distortion

The limits on Total Harmonic Voltage Distortion (THVD) at the connection point are listed in Table 2.

Voltage Level	Total Harmonic Voltage Distortion (%)
LV	2.5
MV	2.0
38kV	1.5

Table 2: Voltage Distortion Limits.

These limits are important in the context of any power electronics controllers being used in the generator system. Power converters are non-linear devices, which inject harmonic currents into the network. The magnitude of these harmonic currents must be limited in order to avoid exceeding the THVD limits, particularly in relatively high impedance distribution networks. Power converters typically incorporate grid-side filters in order to reduce the harmonic currents injected to the grid to acceptable levels, however if the grid connection is weak and has a high impedance, the THVD may exceed the required limits and further filtering may be required.

Maximum Voltage Levels

The maximum allowed voltage levels at the PCC are outlined in Table 3.

Nominal Voltage	Maximum Voltage
230V	253V
400V	440V
10kV	11.3kV
20kV	22.5kV
38kV	43.8kV
110kV	120kV

Table 3: Maximum voltage levels at connection point

The pulsating nature of wave energy and its high peak to average power characteristics can result in significant voltage variations at the PCC, unless some power smoothing is implemented. This again suggests the requirement for some variable speed control capability and/or power electronics converters with electrical energy storage

Reactive Power Requirements

For relatively low power generators and farms (<5MW) and/or those connected to loaded bus bars or distribution lines, the only reactive power requirement is that the power factor measured at the PCC be between 0.92 and 0.95 for active power outputs between 65% and 100% rated. This requirement is relatively loose and would allow most generator types to be utilized. However, for larger generators, connected to dedicated MV/38kV power station bus bars, or to the 110kV network, a wide range of reactive power capability is required. An example of this requirement is illustrated in Figure 2, for Type B generator connections, i.e. generators with rated power output >5MW and connection to a dedicated MV/38kV power station. Moreover, for these larger generators, some level of voltage regulation is required which imposes a requirement on the generator system for controllable reactive power output.

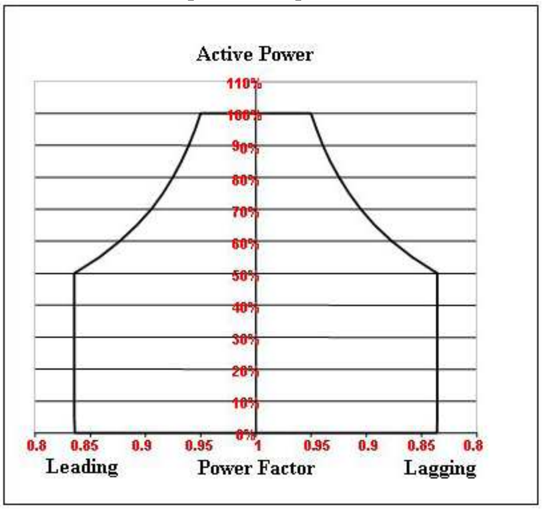

Figure 2: Reactive Power requirements for Type B generators.

Fault Ride-Through Requirements

The requirement to remain connected to the grid during network faults is a requirement that is now being imposed on wind turbine farms >5MW, and there is no reason to believe that the situation will be any different for wave farms. For such turbines connected to the MV/38kV network, the voltage-time profile during which the generator must stay connected is illustrated in Figure 3. Moreover during the voltage dip, the generator is required to provide active power output in proportion to the retained voltage, and also to maximize the reactive current output to the distribution network, within the limits of the generator. This ride-through capability requirement has a significant impact on the generator selection.

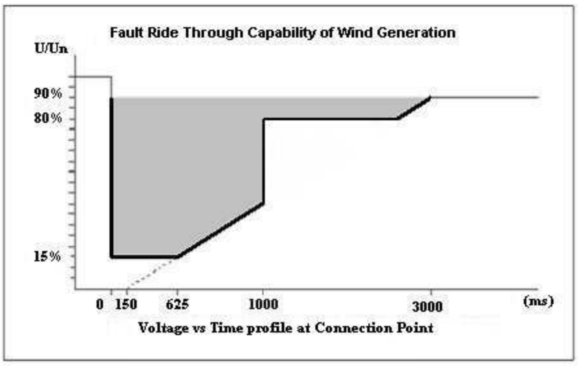

Figure 3: Fault ride-through capability for wind turbines >5MW connected to the MV/38kV distribution network

Active Power Control Requirements

For generator farms with outputs >5MW, the ability to control the active power output, both in response to grid frequency changes and in response to on-line set points from the system operator, is required. Moreover, the rate of change of power must also be controllable, within the limits of the renewable energy source rate of change. It is also specified that the power control must be carried out by proportional variation of power output in individual generating units, rather than switching in and out of individual units.

These requirements place constraints on the generator control system rather than on the specific generator technology itself. For instance, controllable blow-off or bypass valves to reduce power output, or aerodynamic/hydraulic power control through prime mover speed changes, are likely to be necessary.

Implication of Distribution/Grid Code Requirements for Generator Selection and Control

If it is assumed that the proposed wave farms will operate at total power levels greater than 5MW, then the reactive power and fault ride-through requirements described previously effectively eliminate the possibility of utilising fixed-speed direct grid-coupled generators. The direct grid-coupled self-excited induction generator cannot provide reactive power to the grid, nor can it maintain its magnetization through a sustained voltage dip, without an external reactive power and voltage support mechanism, such as a Static VAR Compensator. However, the likely requirement for wide ranging speed control in order to optimize power take-off and provide means for active power control, further militates against this option. Likewise, although the direct grid-coupled SG can provide reactive power and fault ride-through, it has no speed variability, which militates against this choice from the point of view of energy efficiency and mechanical robustness. The fault ride-through performance of the DFIG has come under considerable scrutiny, due to its prevalence in wind turbine generators. It has been shown to be significantly more sensitive to grid faults than those generator options with a full power electronics conversion interface [10]. The author has also published material indicating the potential unsuitability of the doubly fed induction generator for offshore wave energy devices due to its maintenance requirements [6].

In summary, assuming a farm power output of >5MW, it would appear that generator options that include a full power electronics conversion interface between the generator and the network are the most suited to the wave energy converter under consideration, as a result of the following considerations:

- The requirement for variable speed control in order to optimize power take-off, reduce flicker, smooth output power, and provide active power control as required by the distribution code.
- The requirement for controllable reactive power output and voltage regulation
- The requirement for reliable fault ride-through operation

These issues are summarised in Table 4.

Generator Type	Grid Connection Issues
Direct grid-coupled SCIG	Cannot provide reactive power control, fault ride-through, or voltage regulation. A very limited speed control range is possible for flicker reduction and grid power smoothing.
Direct grid-coupled SG	Can provide reactive power control, voltage regulation and fault ride-through. No speed variability, so power smoothing for flicker and voltage distortion control is not possible.
DFIG with rotor power electronics	A reasonable speed control range is available for power smoothing and flicker reduction. A limited amount of reactive power control and ride-through is possible.
SG/PMG/SCIG with stator power electronics	A wide speed control range is available for power smoothing and flicker reduction. Voltage regulations, significant reactive power control and fault ride-through are available. Power electronics trip current levels may result in early disconnection when feeding a heavy fault.

Table 4: Generator Issues

Dynamic Models

The developer is also required under the grid codes to supply the transmission operator with dynamic models of the WEC generation plant, to be incorporated into dynamic grid simulations for the purposes of stability and disturbance assessment. The current simulation package in use by the majority of grid operators is PSS/E from Siemens PTI. The development of dynamic models is a complex and difficult process, and is made more so by the multi-dimensional responses of wave energy devices.

4 Grid Connection Case Study

A case study of typical costings faced by a developer in respect of the generator equipment and grid connection has been carried out and is detailed in this section. This case study assumes a 20MW wave farm connected to the Irish distribution network at a voltage level of 38kV. This is considered to be a representative study for early commercial wave farm development, and also represents the upper end of power levels likely to be distribution connected. The location of the case study is placed at the wave energy test site off Belmullet [11], Co. Mayo, along the north-west coastline of Ireland. Bathymetry studies have been carried out at this location, so it is possible to generate a reasonably accurate estimate of subsea cable location and length. The test site location is illustrated in Figure 4 within the red line boundaries.

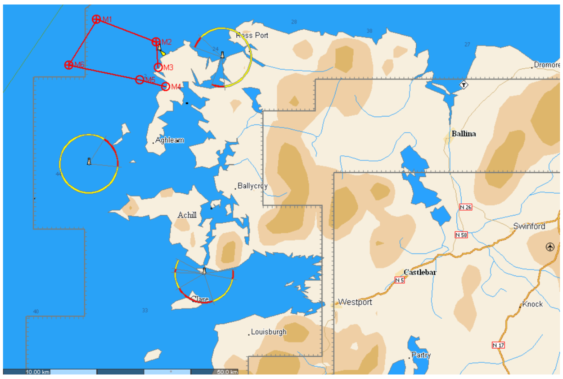

Figure 4: Proposed wave energy test site location

The electrical network layout in the region is illustrated in Figure 5. The power lines in the immediate area are chiefly MV lines with a 38kV connection point available in Belmullet town. This is shown in the left-hand plot. The right-hand drawing only illustrates the local MV distribution lines. The nearest 110kV station, Bellacorick, is about 30km from Belmullet (the first black substation connected to the 38kV line in the left-hand plot).

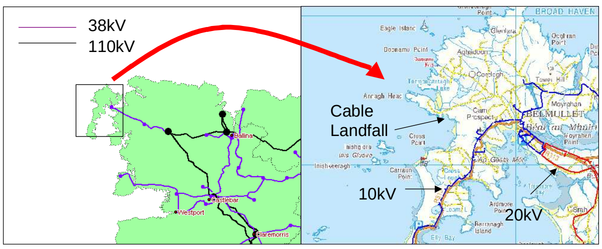

Figure 5: Electrical network layout in Belmullet area

Projected Wave Farm Layout

The projected wave farm layout assumes 20 wave energy devices rated at 1MVA each, spaced approximately 500m apart in an array of 4 deep and 5 across. The area of the farm is thus approximately 3kmx3km. The devices are connected together in groups of 5, with each group being connected to a central floating substation. This scheme is illustrated in Figure 6. The actual implementation of the connection mechanism is not considered here, but is simply assumed to be possible. In similar manner to wind turbine plant, each WEC is assumed to contain an LV/MV transformer and associated switchgear. The cabling between WECs and the floating substation is then considered to be dynamic (flexible) MV cable, which is not required to be buried, due to the unlikely presence of trawlers or anchors within the boundaries of the wave farm. A floating substation is proposed since it is likely to be more cost effective than a fixed structure at 60-90m water depths, and since a seabed connection device is highly non-standard, and requires significant diver involvement with the associated health and safety issues and costs. The cable to shore will be a static 38kV rated cable, which will require rock protection over 1km of its length [11], and will be buried where the seabed permits.

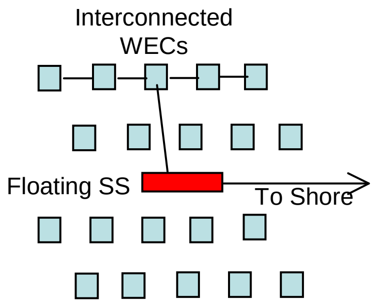

Figure 6: Wave Farm Layout

Offshore Electrical Equipment

Apart from the electrical equipment on board each WEC, consisting mainly of generator, power conversion, control and safety equipment, transformer and switchgear, the main offshore electrical equipment is located on the floating substation. This will consist of two 10MVA MV/38kV step-up transformers with associated busbars, disconnect switches, connectors, and protection circuit breakers. An LV tapping, DC supply and some level of UPS backup are also likely to be required.

Onshore Electrical Equipment

The onshore equipment is projected to be located in a new substation at the nearest point possible to cable landfall. It will consist of the following items:

- 38kV busbar
- 38kV switchgear (CBs, CTs, VTs, Disconnects)
- Metering equipment
- Control room with SCADA controller and satellite communications unit
- Small LV house supply transformer and DC UPS

It is estimated that a 100mx50m plot will be adequate for this size of substation, including access and parking facilities. This will mark the limit point of the developer connection assets.

Network Upgrade Equipment

In this particular case study, the network operator will be required to install approximately 9km of new 38kV line from the onshore substation connection point to the nearest 38kV connection in Belmullet town. This is assumed to be overhead line, and the conductor type is selected to be 150AAAC, based on the power export requirement. The substation in Belmullet contains a single 5MVA 38kV/MV/LV transformer [11], so it is likely that an extra 38kV cubicle will be required for the incoming connection, with its own switchgear. The existing 38kV line from Belmullet to Bellacorrick is a 100SCA rated overhead line. It is likely that this line will also have to be upgraded to 150AAAC, since the predicted regional winter peak MVA in 2012 is only 8-10MVA. Hence, in off-peak times, when the wave farm is generating at full capacity, the 38kV line may have to export close to the full 20MVA.

Costing Methodology

The majority of the grid connection equipment costings have been taken from the standard costings provided by the Irish Commissioner for Energy Regulation (CER) for new generators in 2009 [12]. Cable lay cost estimates have been sourced from ABB estimates, and from [13] and [11]. Generator and on-board equipment costs have been derived from [14] and [15] with 2002 costs escalated to 2009 levels using the Producer Price Index for the appropriate equipment types, as provided by [16]. Land costs and civil works costings have been estimated from average current Irish prices and have been validated against similar costings for the Wave Hub development in South West England [17].

Since the grid connection point is on the distribution network, the charging methodology will be deep, and so the developer will be exposed to all of the costs outlined in this section, including the cost of uprating the existing 38kV line between Belmullet and Bellacorrick. The results of this case study are illustrated in Table 5. A further breakdown of the costs is provided in Table 6.

Item	*Details*	*Quantity*	*Units*	*Cost*
On-board Equipment				
Generator	SG	20,000	kW	€1,048,592
Power Converter	Full Power Elec	20,000	kW	€2,319,063
Controller		20	unit	€1,433,136
LV Switchgear		20	unit	€208,709
LV/MV Transformer		20,000	kW	€760,693
MV Switchgear		20	unit	€237,160
Offshore Electrical Equipment				
Device to Floating Substation Cable	Supply only, MV dynamic cable, 3 core	17.5	km	€2,100,000
38kV subsea cable	Supply only, static cable, 3 core	8.7	km	€1,131,348
Cable laying basic/trenched	Assume main cable is trenched and interdevice dynamic cables basic lay	25.2	km	€4,571,157
Cable laying rock protected		1	km	€961,538
Floating Substation Construction and Deployment	Estimate	1	unit	€500,000
Floating Substation Switchgear	2x 10 MVA trafos MV/38kV, +2 x MV cubicle incorporating protection	2	unit	€1,252,980
Onshore Equipment				
Cable Landfall Civils	Assume substation 500-1000m from beach, approx 1month civils			€25,000
Shoreline Substation Land Purchase	100mx50m Plot	5,000	m^2	€20,000
Shoreline Substation Construction	Fencing, switchyard, Car Park, Metering/SCADA building.	Estimate		€130,000
Shoreline Substation Switchgear	38kV cubicle incorporating protection, disconnects, and civils			€159,590
Shoreline Substation Metering				€59,110
Shoreline Substation SCADA/Control	Assume Satellite unit and UPS required. DSO costs used although TSO RTU required at this power level	1	unit	€58,060

Overhead Cable to Belmullet	38kV overhead 150AAAC	9	km	€814,419
New equipment in Belmullet substation	38kV cubicle in Belmullet SS	1	unit	€159,590
Uprating of 38kV overhead line to Bellacorrick	Upgrade this line from 100sq to 150sq. Assume 50% costs as new poles not required.	30	km	€1,357,365
On-board equipment		31	% of total	€6,007,353
Grid Connection equipment		69	% of total	€13,300,157
Grand Total				**€19,307,511**

Table 5: Costing case study results

Breakdown of equipment	Cost	% of total
On-board electrical equipment	*€6,007,353*	31
Off-shore cable supply	*€3,231,348*	17
Off-shore cable laying	*€5,532,695*	29
Off-shore grid connect equipment (excl cable)	*€1,752,980*	9
On-shore grid connect equipment (excl line)	*€586,350*	3
On-shore overhead line	*€2,171,784*	11

Table 6: Breakdown of electrical equipment costs

It is evident that the grid connection equipment represents a substantial cost outlay, and in fact makes up approximately two-thirds of the entire electrical equipment costs.

5 Conclusions

Some of the more significant technical and financial challenges associated with the grid connection of ocean energy wave farms have been outlined in this paper. These have been firmly embedded in the context of typical grid operator requirements and charging regimes, and have been treated in terms of challenges associated with the generator equipment, and those specifically linked to the grid connection regime.

The grid connection regime has a very direct impact on the financial outlay that will be required of developers. Depending on the depth of the charging regime, developers will be required to fund some proportion of the onshore grid extension work or even upgrades of the existing grid. Furthermore, location dependent UoS charges can have a potential negative impact on site selection for device deployment.

On the generator side it has been shown that the connection codes have important implications for the type of generator equipment and controller performance that will be required. The likely requirement of full power electronics conversion systems is an element that impacts on cost, volume and reliability.

Finally, a case study of a typical medium term wave farm deployment on the Irish distribution network has been outlined. The generator and connection equipment has been outlined along with a detailed breakdown of the cost structure. It was shown that the grid connection costs account for 69% of the total electrical equipment budget. Of this, the offshore cable laying, not surprisingly, makes up the largest portion. The impact of the deep charge regime is evident in the very significant cost proportion also associated with the upgrade of the onshore overhead line.

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