OREGON WAVE ENERGY TRUST
UTILITY MARKET INITIATIVE

TASK 4.5.1: TECHNICAL AND OPERATIONAL BARRIERS

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The Utility Market Initiative was prepared by *Pacific Energy Ventures* on behalf of the Oregon Wave Energy Trust.

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About Oregon Wave Energy Trust

The Oregon Wave Energy Trust – (OWET) - with members from fishing and environmental groups, industry and government - is a nonprofit public-private partnership funded by the Oregon Innovation Council in 2007. Its mission is to serve as a connector for all stakeholders involved in wave energy project development - from research and development to early stage community engagement and final deployment and energy generation - positioning Oregon as the North America leader in this nascent industry and delivering its full economic and environmental potential for the state. OWET's goal is to have ocean wave energy producing 2 megawatts of power - enough to power about 800 homes - by 2010 and 500 megawatts of power by 2025.

ECOFYS

Report for:
Oregon Wave Energy Trust – Utility Market Initiative
Technical and Operational Barriers to Integration of Wave Energy

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Introduction

The purpose of this task is to identify the characteristics of wave energy and the potential technical and operational barriers they may pose to the utility integration of the wave energy projects. The analysis identifies both the potential issues facing wave-power integration and the applicable standards for addressing those issues. This report is organized into five sections:

I. Wave-Energy Resource Characteristics
II. Potential Interconnection Issues
III. Technology Review
IV. Applicable Standards and Technical Provisions
V. Conclusion

The analysis does not assess the technical and economic potential of wave power generation and, hence, does not quantify the scale of development that may be expected in the future. Of course, strict, specific requirements may be inappropriate as long as wave-power generation is a niche technology with limited impact on the network. However, technical regulations must not discriminate (also from a technology point of view), and must anticipate further development in order to avoid frequent amendments.

Finally, the analysis does not provide a comparative assessment of the particular wave-power technologies discussed or, more specifically, their electrical concepts. Such a detailed analysis goes beyond the scope of this task. Rather, the generic analysis set out here provides the proper basis for individual developers to further elaborate on their electrical concepts.

I. Wave Energy Resource Characteristics

During the last decade it has been acknowledged that the increasing number of distributed and renewable based generators has introduced new challenges for the safe, reliable, and economic operation of power systems. Generally, the challenges can be related to four characteristics frequently associated with distributed generation, particularly when the generation is based on renewable resources.

- ***Different electrical behavior:*** The electrical machinery used in distributed and renewable-based generation is limited in unit size. For a variety of technical reasons these generation technologies in most cases do not rely on conventional synchronous generators, like those used in large-scale power generation. Due to both of these aspects, distributed generators respond in a different way to system disturbances than large power plants. A prominent example is the issue of low voltage ride through capabilities. In recent years, this issue has been addressed and resulted in specific requirements for distributed generation.
- ***Electrically remote:*** Often distributed and renewable-based generation are implemented far from load centers. For obvious reasons, wave energy can only be installed in coastal areas. From there the power has to be transmitted to end users. The infrastructure has to facilitate the resulting load flows. Additionally, protection schemes must be adjusted and the impact of the additional transmission assets on the dynamic behavior of the overall network has to be managed.
- ***Fluctuating (renewable) resources:*** Fluctuations in the time frame of hours or days, affecting plant scheduling, are discussed elsewhere in the report. However, wave-power generation may also result in load flow fluctuations in the domain of seconds and may cause enhanced flicker levels. In order to avoid stress for network components or power-quality problems, these fluctuations have to be managed adequately and have to be taken into account in the connection process.
- ***Limited accuracy of renewable-generation scheduling:*** This affects the scheduling of all players in the market. It is a system-wide issue and does not directly affect the connection planning and operation of transmission assets. This issue is addressed in more detail in Task 3.3, Value vs. Cost of Wave Energy and in Task 4.4, Scheduling Parameters.

II. Interconnection issues for wave-energy converters

Major potential issues related to network integration of wave-power converters are:

- ***Power quality*** - Introduction of the new generation must not result in violation of voltage tolerances. Also, the tolerances for higher harmonics have to be respected in order to avoid adverse effects, such as increased transmission losses and stress for components.
- ***Reliable supply*** (also in case of congestion) - This means, among other things, that minor network disturbances should not trigger a substantial loss of generation. Additionally, the voltage stability of the network should not be compromised by the additional assets.
- ***Safety*** - Adequate protection and anti-islanding schemes have to guarantee safety of staff and the general public.
- ***Cost*** - Adjustment of the existing infrastructure to the changes triggered by introducing new generation may also imply some extra investments, not strictly related to the generation itself.

These issues are somewhat interrelated. Harmonic distortion may be mitigated by investments in filters. Additionally, adequate measures may affect generator design or network design and operation. In some cases, solutions may be found at both sides.

The following table indicates how these issues are related to the specific characteristics of wave-power generation as discussed in the previous section. The table also illustrates that the renewable, and more specifically fluctuating, character of wave power interacts only with some of the issues to be considered.

	Different electrical behavior of equipment	**Electrically remote**	**Fluctuating generation**
Power quality			
Harmonics	Electronic power converters		
Flicker		Charging currents for offshore transmission (switching operations)	Power fluctuations
Voltage control	Reactive power control	Overvoltages related to: - switching operations - long transmission distances - reactive power control	
Reliable supply			
Fault currents		May be higher than usual, conventional network planning task	
Voltage ride through capability	Control and design of generator and electronic power converter		
Voltage stability	Reactive power response to network disturbances	Potentially long cable sections may adversely affect voltage stability in the network	
Safety			
Protection schemes	Limited short circuit capacity of generators: differential protection may be required	Generation in underlying network sections: differential protection required	
Unintended islanding	Generator protection scheme (state of the art)		
Cost			

Table 1. Interconnection Issues for Wave-Power Generation

Only the aspects in the first column are related specifically to the wave-power generation technologies and, in particular, the electrical concept applied. The issues in the second and third columns concern generic aspects of proper network planning triggered by distributed generation. They are discussed only briefly here.

Wave-energy projects in Oregon have a limited number of electric utilities to which they can interconnect. Not all of these utilities have an interest in purchasing the energy, so a natural consequence many wave-energy projects will face is wheeling. There are both technical and economic implications of wheeling the power output of a wave-energy project across the system of one or more utilities to reach the end customer.

From a technology point of view, wheeling raises several of the issues identified in column two of the table above. Sending power long distances over transmission lines that were not initially designed for this task can lead to voltage control problems and potentially higher fault currents. Particularly in Oregon, if wave-energy installations reach the scale of hundreds of megawatts, transmission operators will likely see power flows reverse at times on the transmission lines between the coast and the load centers in Portland and the Willamette Valley. Since wave energy is known to vary seasonally, the operators of the transmission systems that wheel the power will face the typical challenges of monitoring for congestion and providing for adequate system protection schemes, made more complicated by the need to change procedures and possibly even equipment configurations in response to the varying output of the wave-energy projects.

These additional actions required of the system operators do not come for free. Taking wind power as a reference, the typical rural electric co-op in Oregon charges ~ 0.5 cents/kW to wheel the output of a wind farm over their system. Depending on the coastal utility providing the wheeling service, this figure may be considered a good rule-of-thumb for developers. But the operational characteristics of wave-energy projects have yet to be fully understood, and only experience with real projects will prove the full extent of system impacts.

In general, wheeling power adds another layer of complexity to the interconnection process which often extends timelines and adds cost. The wheeling utility may have different operational strategies from the purchasing utility, which need to be worked out contractually. The interconnection studies will likely involve personnel from both the wheeling and the purchasing utility, which necessitates extra communication and harmonizing of approach. Finally, in addition to the fee for wheeling the power produced by the facility once it is operational, developers may need to pay for additional system upgrades to the wheeling utility as part of the interconnection agreement.

III. Technology review

Before reviewing the potential interconnection issues related to wave-power conversion, it is helpful to distinguish between the distinct technology concepts. General categories are:

- Oscillating water column in a near shore structure. Examples are the Wavegen devices of Voith Hydro and the technology developed by Ocean Linx. Typically these devices are constructed close to shore and, consequently, grid connection does not require cabling of a significant length. For full-scale commercial converters, the capacity of each unit will be in the range of some hundreds of kW to a few MW. Linear arrays of several units are possible, but the extension of generation sites may be limited because of the implications of the civil constructions associated with this technology approach. The electrical concept relies on conventional rotating machinery. Still, the fluctuating input combined with the technical code requirements will strongly encourage application of electronic power converters.

- Hydraulic concepts with onshore power conversion. Examples are the CETO devices of Carnegie Wave Energy Limited and Aquamarine Power's Oyster® wave-energy converter. These devices are placed a reasonable distance from shore as well, but because power conversion is located onshore, transmitting power to a connection point with the network includes only conventional assets. The capacity of each unit will be in the sub-MW range, but array configurations are an inherent feature of the technology concept. The hydraulic transmission allows for integrating short-term energy storage and thus enables the smoothing of power output to a larger extent than just the natural effect of combining a number of devices. The electrical concept is based on conventional rotating machines. From the perspective of interfacing with the grid, these power generation concepts are quite conventional.
- Offshore devices with electrical power conversion offshore. Examples of this technology approach are the buoy type converter of Columbia Power Technologies, the PowerBuoy® of Ocean Power Technologies and the linear converter arrangement of Pelamis Wave Power. These concepts use custom-designed electrical generators, e.g. linear generator arrangements, possibly with permanent magnets. These generation technologies regularly use electronic power converters. Because power generation takes place offshore, the concept may imply longer cables for transmission.

The information published by the technology developers does not describe the electrical configuration in detail. For that reason, the options and implications are described only generally here.

- Synchronous generators directly coupled to the grid: These generators are applied in large power plants. For various reasons, their suitability for wave-power generation is limited. They have to be operated with constant speed and, with conventional design, power fluctuations in the drive train are translated directly to fluctuating power at the terminals. As a result the machinery is exposed to high mechanical loads and conversion efficiency cannot be optimized for changing power input. Hydraulic, variable-speed fluid couplings (e.g., those manufactured by Voith) overcome this disadvantage.

- Synchronous generators with full-capacity electronic power converters: By adding a power converter between the generator and the terminals of the grid generator, speed and network frequency are decoupled. This allows for smooth and optimized operation of the drive train without compromising conversion efficiency. Synchronous generators may be excited electrically or by permanent magnets, and they may have a circular or a linear geometry. These design choices do not interfere with the aspects to be considered when integrating to the network.

- Induction generators / asynchronous generators: These generators are widely used in the wind industry. State of the art generator concepts include some electronic power conversion (e.g., 'doubly fed induction generators' / DFIG). Due to patent-infringement issues, several wind turbine manufacturers still supply induction generators directly coupled to the grid for use in North America, but even with advanced controls they have obvious technical limitations. This will apply for wave-power generation, too. DFIG concepts allow for highly efficient, variable speed operation.

Of course, the operation and maintenance of electrical equipment in a moving, possibly submerged structure represents an engineering challenge. This applies to rotating machines or linear generators as well as to power electronic converters. Accessibility offshore is limited. In order not to compromise yield, availability and reliability of all components has to be extremely high. As similar challenges apply to offshore wind, the wave-power community can profit from the lessons learned in this slightly more advanced business.

IV. Applicable standards and technical provisions

Important standards related to the grid integration of wave energy conversion devices are IEEE 519-1992 (Harmonics) and IEEE 1547-2003 (Interconnection of Distributed Resources). Additionally, the technical requirements defined in FERC Order No. 661-A "Interconnection for Wind Energy" will most likely apply to industrial-scale wave power. At the very least, the requirements will serve as a starting point for more dedicated provisions once large-scale development of wave-power conversion starts.

The following list of issues highlights some, but not all, of the aspects requiring special attention.

- Of course, the rating of the power lines must ensure that the **load flows** can be managed without violating the **voltage tolerances** or the **thermal ratings** of particular assets. The correlation of the output of several wave-power facilities in an area may be significant. Additionally, there may be a correlation in the output of wave-power plants and wind farms in the region. From this perspective, respective grid connection studies may need to include larger network sections.

- The reference point for **voltage and reactive-power** considerations is the point of common coupling (PCC) with the existing distribution or transmission network. In the case of wave power, this implies that the voltage profile in the offshore part of the generation site is subject to the design considerations of the developer. Consequently, no capabilities with respect to voltage or reactive-power control are required from the individual devices. Additionally, experience shows that respective control tasks can be implemented less expensively and more efficiently with conventional components at the PCC.
    - ➢ A generating plant shall maintain a power factor within the range of 0.95 leading to 0.95 lagging, measured at the Point of Interconnection, but only if the Transmission Provider's System Impact Study shows that such a requirement is necessary to ensure safety or reliability. On the other hand the standard (IEEE 1547-2003) clarifies that active power control at the PCC is not allowed.

- The **grounding** design must ensure that no overvoltages are caused that exceed the rating of the equipment at the PCC and in the underlying network. Additionally, the design shall not disrupt the coordination of the existing **grounding fault protection** in the existing network. Because wave-energy generation may cause a temporary reversal of power flows in particular network sections, the protection scheme must be reviewed anyway.

- The common rules for **synchronization** and **protection against unintended islanding** apply.

Low Voltage Ride Through (LVRT) The most important challenges will result from low voltage ride through requirements as defined in FERC Order No. 661-A "Interconnection for Wind Energy." In the current regulatory environment, these requirements do not apply to small scale projects with a cumulative capacity less than 20 MW. For wave-power demonstrators in the near future this means that the technology does not need to meet the specifications. However, when wave power becomes mature, respective requirements will certainly apply. Additionally, implementing substantial amounts of distributed generation at lower voltage levels creates a need for similar provisions in distribution codes. These requirements have direct implications for the design of the electrical equipment and for generator control.

Voltage ride through capabilities have to ensure that generators do not trip as a consequence of a network disturbance that is cleared regularly. The objective of this requirement is to avoid minor events that may result in a short-term voltage disturbance, in turn tripping large numbers of generators. This might result in substantial loss of generation, and as such the lack of LVRT capabilities creates a risk for system stability.

The first LVRT requirement implemented by the Federal Energy Regulatory Commission (FERC), was Order No. 661 (June, 2005). It specified a voltage–drop duration curve describing the system's response after a fault. For operational states above the curve, generators are not allowed to trip or to cease generation. The voltage is measured at the high voltage terminals of the plant transformer. Wind generators were not required to stay on line if system voltage dropped below the bottom of the curve (15% of nominal voltage), even momentarily. The requirements of FERC Order No. 661 are illustrated in the figure below.

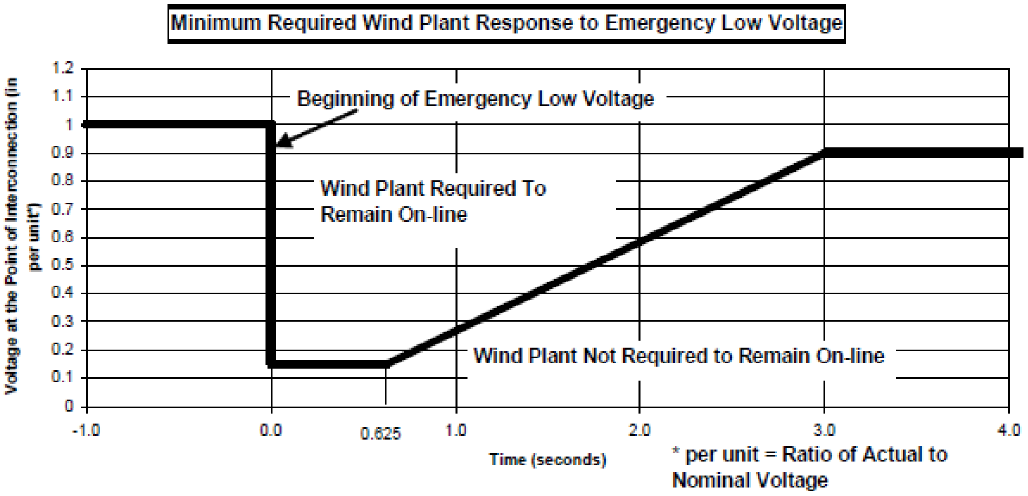

Figure 1. FERC Order No. 661 – Low Voltage Ride Through requirements

Not long after issuing Order No. 661, FERC issued a revision, Order No. 661-A "Interconnection for Wind Energy" (December, 2005). FERC Order No. 661-A requires that new installations must remain online for voltages as low as zero, lasting up to 9 cycles (0.15 seconds). Order No. 661-A does not specify the requirements during the post-recovery period, as Order No. 661 did. (Requirements during the post-recovery period are allowed to vary depending on electrical system characteristics.) These two details have caused heated debate between the wind industry and regulators, but the Order stands and is the LVRT requirement that is enforced by utilities before allowing interconnection of a wind farm larger than 20 MW.

This standard is not retroactive, but is required for all new wind farms coming online after the issue date of the Order. Since implementation of Order No. 661-A for wind farms, FERC has stated that the requirement should be implemented for all large generators, regardless of technology. The North American Electric Reliability Corporation (NERC) seems to be backing up this interpretation, and is incorporating the requirements of Order 661-A into the upcoming NERC standard PRC-024, Generator Performance During Frequency and Voltage Excursions, currently in the final stages of approval. An important difference between the two regulations is that the NERC PRC-024 will provide definition on how generators are required to respond to specific voltage levels during the recovery period. With the NERC standard being technology independent, other industries including conventional generators and solar photovoltaics are engaging in the development of this next critical requirement for LVRT. Some important questions must be answered, such as "How do auxiliary loads stay online during the zero voltage period?" and "If the entire power output of the generator passes through a power electronic converter, what exactly does ride-through mean?" These questions are applicable to some of the existing wave energy technologies as well.

Capabilities that are covered in other international grid codes or that are under consideration are:

- Voltage support / reactive power control in case of voltage drop
- Generator response to frequency excursions

When accepted and adopted by the industry, similar future requirements may also apply to wave-power generation. Nevertheless, at this time the specific characteristics of wave power have to be taken into account and may lead to slightly differing provisions. One illustrative example of justified deviations between the wind code and requirements for wave-power generation is the reference point for voltage measurement. Offshore installations (e.g., the PowerBuoy® of Ocean Power Technologies) have the plant transformer offshore and are connected to the onshore network via submarine cables. In such a case it may be more reasonable to measure the voltage drop associated with a network fault at the point of common coupling onshore.

V. Conclusions

- There are no fundamental problems associated with grid network connection and system integration of wave-power generation.
- Granularity and overall size of generation facilities in a mature stage will be similar to offshore wind farms. This is a proven technology and industry solutions are available.
- With some exceptions, technical standards similar to (offshore) wind will apply to wave power generation. These standards are still developing and, hence, the current framework represents only a starting point for further elaboration and evaluation of technical designs.
- Some of the wave-power generation technologies are less challenging from a grid integration perspective because they rely on near-shore or onshore siting of the electrical equipment.
- Most likely, knowledge transfer from the wind community to the wave-power community will help to avoid mistakes and minimize development costs.