Mobile Wave Energy Harvesting System

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ABSTRACT

This paper presents an economically viable, alternative method of harvesting ocean wave energy, comprised of a boat with an on-board wave energy harvesting system, and on-board energy storage capacity. A typical system consists of 50 meter boat with 1 MW capacity of wave energy harvesting equipment and 20 MWH of energy storage capability. Operationally, the boat cruises to a favorable location off-shore, harvests energy for approximately 20 hours, cruises back to shore, connects to the electricity grid, and releases the stored energy during high demand periods. Preliminary calculations promise electricity cost of US$0.15/KWh. The system offers numerous advantages including no expensive undersea cables, no permanent sea structure, easy maintenance, simplified permitting, and better survivability.

Keywords: wave energy, wave power, renewable energy, ocean energy

1 BACKGROUND

Environmental damage related to fossil-fuel generated electricity has driven interest in renewable energy such as wind and solar. At about $0.10/KWH, wind is very cost competitive but frequently requires long transmission lines from wind source to point of use. Solar eliminates transmission lines by placing the solar panels at the point of use, but at about $0.30/KWH is still a niche technology. So the search for other renewables continues.

A large portion of the world's population lives near the ocean's coastlines meaning that if electricity could be generated from the ocean, it would be easy to transmit to population centers. Electricity can be generated from waves, water currents, and ocean thermal energy, with wave based energy being arguably the most promising.

The beginning of the modern wave energy development efforts started with Yoshio Masuda[1] in Japan in 1940. Masuda's navigation buoy had some commercial success but the fact that modern navigation buoys are solar powered says something about the limits of existing wave power technology.

Modern wave power technology is at a pre-commercial development stage with only a handful of pieces of equipment actually in the water. The floating Pelamis [1] device is long (140m) and snakelike in appearance and extracts energy from three articulated joints and was first connected to the grid in 2004. The near-shored sea-floor mounted Oyster[1] device works with a pitching/surging motion and has been on trial in the UK since 2009. The Wavebob[1] device uses a heaving "point-absorber" type of technology commonly seen in wave power technology. Although trials started in 2006, the Wavebob technology has yet to garner much support.

2 OBSTACLES

Ocean wave energy development has had a number of significant obstacles in its path. Historically, wind and solar started small and gradually got larger using the fact that the technologies scale linearly to their advantage. Wave technologies are strongly dependent on system dynamics and do not scale linearly. A 1/10th scale model of a wave energy system does not produce 1/10th the energy of a full scale generator, in fact it may not produce energy at all. This has lead to the requirement of either testing a multi-million dollar full-scale model or doing nothing at all. Further exacerbating this problem is the relatively few software tools for analyzing these complex systems or wave tanks suitable for testing the prototype systems.

An additional challenge is underwater power cables costing approximately US$1 million/mile. This is a huge burden for prototype development and a significant system cost burden in the long term. The large fixed cost of the cable forces designers to develop large farms of wave energy collectors to get reasonable $/KWH pricing.

The destructive forces in waves are perhaps the most serious challenge as can be seen in Equation 1.

$$\frac{P}{b} = -\frac{\rho g^2}{32\pi} T H^2 \tag{1}$$

Where P/b represents the power per unit crest wave length, T is the time period between waves, H is the wave height, and the other values can be treated as constants. Note that the power is related to the height of the wave squared. So while typical wave height for a location might be 2 meters, the wave energy collector must be designed to survive the occasional 10 meter high waves that are 25 times more energetic. This "over design" makes the devices much more expensive.

Any permanent ocean structure faces serious regulatory restrictions and is also very expensive to maintain due to the service difficulties for a device designed to move in the ocean waves.

3 CONCEPT

Breaking with the traditional concept of wave energy converters, this paper proposes a mobile wave energy converter that is not permanently connected to the sea floor. To eliminate the issue with expensive power cables, the energy collected will be stored on the vessel. A typical system consists of 50 meter boat with 1 MW capacity wave energy harvesting equipment and 20 MWH of energy storage capability, shown conceptually in Figure 1. Operationally, the vessel cruises to a favorable location off-shore, harvests energy for approximately 20 hours, cruises back to shore, connects to the electricity grid, and releases the stored energy during high demand periods. The vessel would dock at existing marine docks meaning very little new infrastructure would be needed.

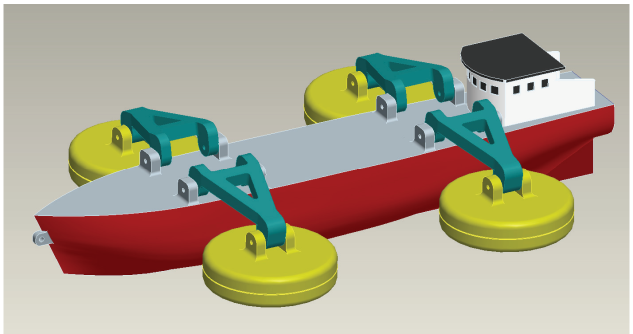

Figure 1: Conceptual design of wave energy harvester.

4 STORAGE

There are remarkably large and varied number of energy storage methods in service in the world. Depending on the technical and economic challenges, energy may be stored either: mechanically in a spring, flywheel, or gravity; or as chemical energy in a battery; or as electrical energy in a capacitor; or as thermal energy in salts, to name just a few examples. The best method to use for any application depends on a number of factors including how long the energy must be stored, efficiency, reliability, cost, and ease of integration with the rest of the system.

For the current application, one critical factor for success is energy density. After all, the energy storage system must fit on the vessel. Energy density comes in two forms, 1) specific energy density (based on weight) and 2) volumetric energy density. Both factors must be considered. If the storage system is too heavy, the vessel will sink. If the storage system is too large, it will not fit within the vessel.

As a starting point for a conceptual design, a 150 foot (46 meter) long vessel with 20MWH of storage was chosen. A vessel of this size can carry approximately 750 tons (682,000 kg) and a volume of 159,000 gallons (600,000 liters). Therefore the energy storage system needs to have a minimum energy density of 106 kJ/kg and 120 kJ/liter.

Approximately fifteen different energy storage technologies were selected for investigation. For each technology, the best commercially available exemplars of the technology were investigated to determine (or estimate) the storage density. Note that this density is often much lower than the density numbers discussed in academic settings. Actual products require mechanical support, housings, heat exchangers, etc. that all significantly decrease density. In cases were commercial exemplars where not available; estimates of density were made using basic principles of physics, e.g. gravity.

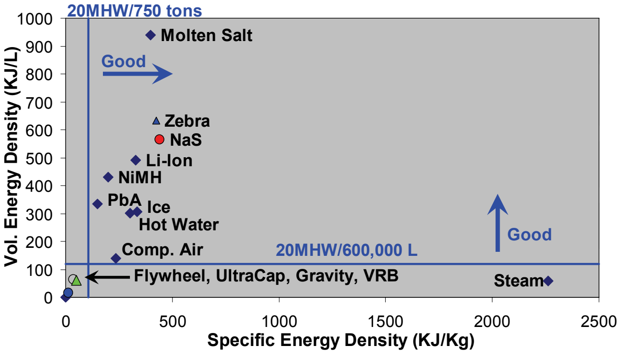

Figure 2: Energy density of storage technologies

The energy densities of the various storage technologies can be represented by a chart with four quadrants as shown in Figure 2. The technologies in the lower left quadrant have such low density that they would neither fit in the vessel nor allow it to float. These technologies include flywheels, gravitational storage, and ultra-capacitors. (Naturally, ultra-capacitor technologies may work in the future whereas gravity will not change.) Technologies in the upper right hand quadrant have adequate energy density for this application. These technologies include a number of battery chemistries, thermal storage (e.g. molten salt), and compressed air.

The next step in narrowing the choices is to reduce the battery technologies to one choice, then it can be compared to other non-battery technology.

Batteries have at least four technical limitations that effectively increase their installed cost per unit time. 1) *DOD (depth of discharge) limitation*. Most batteries cannot be fully charged and fully discharged without significantly shortening their life. 2) *Cycle life limitation*. If the battery pack cannot last 10 years worth of daily cycling, it would need replacement. 3) *Efficiency*. Not all of the energy stored in the battery can be retrieved. 4) *Self discharge*. Energy stored in a battery dissipates over time. Each of these limitations requires that a larger battery than initially planned will need to be purchased. To deliver 20MWH worth of energy to the grid, a battery pack between 30MWH and 35MWH would need to be purchased depending on the technology.

The analysis showed some surprising results. Lead acid batteries have a very low $/KWH price, but are actually more expensive in the long term due to necessarily frequent replacement.

Overall, the relatively unknown NaS (sodium sulfur) battery technology was found to be the most cost effective with the well-known Li-Ion battery technology being a close second.

But batteries are not the only possible storage technologies, there is also compressed air and thermal storage (molten salt) under consideration. For each technology, one piece of hardware is needed to convert the energy into the right form for storage, e.g. a compressor. Furthermore, another piece of hardware is needed to convert the energy from the stored form into grid electricity, e.g. a steam turbine generator.

These pieces of hardware were found to have two significant factors that influenced the selection of the best technology; 1) equipment cost and 2) efficiency. If the energy is stored on the vessel in batteries, an inverter is needed to convert the energy into grid electricity. The hardware cost is approximately US$400/KW. In contrast, if the energy is stored thermally, a steam-turbine generator would be needed at a price of US$1700/KW. This difference makes thermal storage less competitive with battery storage. Similar hardware cost issues plagued compressed air storage. However, the larger problem is efficiency.

Many energy conversion technologies have very low efficiency. The best steam turbine generators, for example, can only convert about 40% of the thermal energy in to mechanical work compared to 97% efficiency for electrical inverters. This means that 60% of the energy collected will be discarded in a thermal storage system. To compensate for these losses both the wave harvesting equipment and the energy storage system must be enlarged. In the end, the overall system cost using batteries was found to be dramatically less expensive than either the thermally based storage or compressed air based storage.

NaS based batteries were chosen as the form of storage for this application with Li-Ion based batteries as a close second.

5 SYSTEM DESIGN

Extracting energy from waves is technically very challenging. The direction of movement changes every 5 to 10 seconds, unlike wind that may blow in the same direction for hours. Furthering the challenge is that for offshore wave energy converters there is no stable mechanical reference. There is no solid ground, if you will.

For heaving wave energy converters like the Wavebob, the traditional solution is to make two floating bodies, one of which has a very low natural frequency. This is typically a very large body with deep draft which makes the WEC much more expensive and difficult to take in and out of port.

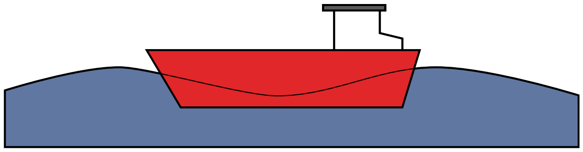

Figure 3: Ship in waves.

For the proposed mobile wave energy harvesting system, the ship itself can act as a relatively stable platform as shown in Figure 3. Depending on the wavelength, the forces on the ship from the crests of the waves are cancelled by the troughs of the waves. This allows the ship to act as a stable reference for some types of wave energy converters.

6 SYSTEM DYNAMICS

The mobile wave energy harvester has complex dynamics that make design iterations difficult. There are three ways that such a system can be developed, 1) using differential equation, 2) using CFD (computational fluid dynamics), and 3) using scale models in a wave tank. Initial development work was done with a differential equation based model of a heaving wave energy converter like the ones shown in Figure 1. This model was useful in understanding the phase behavior between the waves and the heaving buoys, but did not include the ship dynamics. Since few CFD models are capable of handling both floating bodies and waves, a scale model based approach was used for more detailed study of the system behavior.

7 SCALE MODELS

To try out different conceptual designs, a 1:200 scale model wave tank was developed. The tank uses a wedge shaped plunger-type wave generator, an electrical wave height gauge, and a parabolic wave absorber (to kill reflected waves). The tank is calibrated so that scaled waves of known heights and periods can be generated.

Traditional methods of prototyping scale model ships are slow and labor intensive. For this research, a new technique was developed using FDM (fused deposition modeling, or 3D printing). Prototype vessels and buoys could be developed in CAD (Pro-E), printed, and then used directly in the wave tank without additional modifications. This was possible for two reasons. First, the FDM allows the manufacture of hollow, but watertight shapes, as illustrated in Figure 4. Second, the FDM process can be used to create ballast at the base of these shapes so they float at the right level in the water.

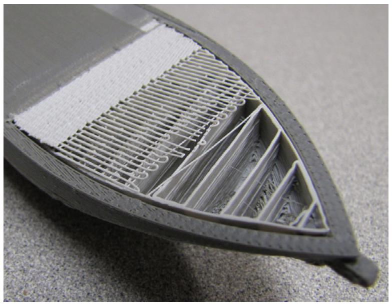

Figure 4: Construction of an FDM prototype.

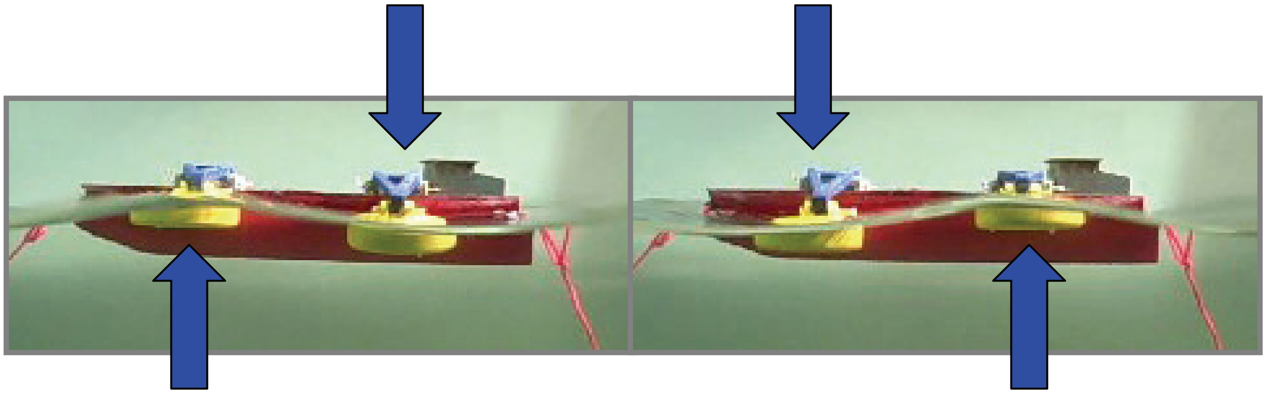

Figure 5: Motion of 1:200 scale model in wave tank

Testing of the scale models showed promising results with the heaving buoys moving in the desired phase relationship to the ship for a range of different water wave lengths as show in Figure 5.

Several other concepts were developed and prototyped in the wave tank. The relative ease with which new concepts could be tested shows the great value of the FDM prototyping process.

8 ECONOMICS

The economics of the mobile wave energy harvester are driven by 1) deployment location 2) cost of capital equipment, 3) operational costs, and 4) operational model.

Deployment location: The best location to deploy this system will have both strong waves and high electricity prices. The value produced by this system depends on how much electricity is produced and the amount the customer is willing to pay for it. Because the energy in the wave increases with the wave height squared, large average wave height will be critical to economic success.

Cost of capital equipment: A significant cost savings with this concept is that existing, perhaps refurbished, vessels could be used. The battery storage will be the single largest expense in the system, so optimizing its cost (and life) will be critical. Significant additional costs come from the custom made wave energy converters (WEC) and the commercially available inverters.

Operational cost and operational model: If the operational model is a single vessel, the expenses are quite high relative to the KWH generated. However, if multiple vessels (say at least 6) are used, the economics improve significantly. This is because the cost of a dock and inverter can be shared among the vessels. Additional labor saving can come from using 6 barges and 1 tug boat. The tugboat would take the barges to and from the dock, rather than six separate vessels with six separate crews. The best possible operational model is still being developed, but it clearly has a significant impact on the economics of the operation.

An initial model of the mobile wave energy harvesting system shows the exciting prospect of producing electricity for US$0.15/KWH is possible. This number is higher than the cost of wind based electricity but significantly less than the cost of solar based electricity. As with all renewables, the cost can be expected to come down as it goes into volume production and the operational efficiencies improve.

9 CONCLUSIONS

Wave energy represents a large untapped resource right near the world's population centers. The slow development of wave energy technologies is a reflection of the technical, economic, and bureaucratic challenges that have faced technologists.

The numerous advantages of the proposed mobile wave energy harvesting system will help mitigate a number of those challenges including

1) Lower costs: no need for underwater cables.
2) Easier permitting: no permanent sea based structures.
3) Schedulability: electricity can be transferred to the grid at times of peak demand.
4) Survivability: the harvester can be left at port during a storm.
5) Distributed energy: the system can be replicated up and down the coastlines.

We all look forward to a brighter energy future for our children. Compared to the current methods of energy generation, a port full of mobile wave energy harvesters would be a beautiful, sustainable sight to see.

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