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Energy Storage Solutions for Offshore Wave and Tidal Energy Prototypes

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Abstract— This paper investigates the motivations for energy storage solutions for offshore Wave Energy Converters (WEC) and tidal energy prototypes. It examines the power and energy storage solutions on offer for developers to aid them during the design stage. Energy storage solutions examined include lead acid batteries, lithium ion batteries, supercapacitors, lithium ion capacitors and diesel for diesel generators. A focus is placed on key installation, operation and maintenance requirements associated with the apparent suitable technologies which are often overlooked. A case study examining a tidal developer's energy storage needs is then presented.

Keywords—energy storage; battery; lead acid battery; VRLA battery, AGM battery; lithium ion battery; wave energy converter; tidal energy.

I. INTRODUCTION

While Wave Energy Converters (WECs) are still being developed, it is important to have other sources of power/energy apart from the main power take-off (PTO) of the device, e.g. on-board solar PV arrays and small wind turbines. Output power smoothing and grid support services are often a key stress of papers examining energy storage solutions for offshore WECs [1], but this paper focuses on the primary operation and survivability of offshore WEC and tidal energy prototypes from an energy storage solution perspective.

II. BACKGROUND

The WEC and tidal industries are still in the development phase with many companies investing heavily in prototype development and advancing through the Technology Readiness Levels (TRLs). These levels serve as a guide to developers which help minimise financial and technological setbacks.

WECs that first enter the ocean for testing typically generate powers in the 10 - 20 kW range. This initial ocean site deployment corresponds to TRL 5 and above.

These devices are typically at the $\frac{1}{4}$ scale level. To predict the generated powers when scaling a prototype device to full size, Froude scaling is used. In Froude scaling, a dimension ratio of $1:\lambda$ results in a power scaling of $1:\lambda^{3.5}$. This gives full scale power ratings of 1.2 - 2.5 MW.

During tank testing on smaller models, constant access to the device is available for modifications. Little electrical work is required from device developers as power levels are low and pneumatic or mechanical powers are analysed and the conversion to electrical energy is avoided. Before WECs enter the ocean, the electrical power take-off (including generator, control strategy, and inverters) is tested, typically in a warehouse or electrical laboratory environment. Due to time and cost restrictions, testing of any included energy storage system is limited. After the deployment of scaled models in the ocean, access to these device prototypes decrease significantly, primarily due to environmental factors and cost of scheduling maintenance access. The need for a reliable energy system with low maintenance intervals for ancillary electrical services needs to be considered, as well as planning the installation, operation and maintenance involved.

To aid developers during this deployment process, wave energy test sites provide or aim to provide many supports that can range from the provision of an electrical connection to dissipate power [2], as well as offer an ancillary power supply [3]. The islanded power platform designed to perform such tasks in Galway in Ireland and described in [2], has not deployed and test site developers here will currently need to consider all the electrical issues for their devices. Even with external auxiliary supply connections, it is important that redundancy is built into any WEC or offshore tidal energy systems, and that they can operate autonomously.

III. DESIGN PHILOSOPHY AND LESSONS OF ELECTRICAL SYSTEMS ON OFFSHORE WEC AND TIDAL DEVICES

A recommended design philosophy of an electrical PTO in an offshore WEC is outlined in [4] and include:

- **Robustness:** This involves absorbing the cost of oversizing critical components as the cost of failures and repair is so high, especially during the test stages of the scaled prototypes.
- **Maintainability:** As experience has demonstrated, issues and failures are very likely in a WEC or tidal prototype. Sometimes general maintenance is also needed. Design optimisation for easy repair, debugging, troubleshooting should be attempted. This includes modular design, provision of spare components and software revision control, as well as detailed software design not only in normal conditions but also in warning, error or failure conditions.
- **Usability:** Examining the likely process of commissioning and work post-deployment by any personnel. E.g. The use of electrical connectors which prevent misconnection.
- **Environmental suitability:** Protection of the components and/or system against sea-water ingress, salt spray, high humidity, condensation and fluctuating temperatures. Also, protection of the environment from the components/system.
- **Safety:** Acknowledging the danger associated with the offshore environment and minimising risks to humans first and equipment second.

Maintenance, installation and usability lessons in [4] from testing a WEC prototype in the offshore environment are summarised here:

- Minimize the work which must be carried out on the offshore device rather than in a workshop on land. As there is limited working space and time aboard, it is very difficult to anticipate all tools and consumables required, and in the offshore floating environment hand-eye coordination suffers.
- Provision of a connection to the electrical grid onshore at a suitable voltage level should be considered for offshore wave energy test sites.

IV. TYPICAL ELECTRICAL LOADS OF WEC PROTOTYPES

Diesel generators have been installed in many WEC prototypes during sea testing, for example, in the FP7 European research project CORES (Components for Ocean Renewable Energy Systems) where an offshore floating 15 kW OWC (Oscillating Water Column) test platform operated for several months off the coast of Ireland (<http://www.fp7-cores.eu/>) [4]. It must seem counterintuitive for wave and tidal energy developers to need to install an on-board diesel generator on their

renewable energy device, and it might be difficult to inform stakeholders. A diesel generator was also the main source of ancillary power described for the power platform in [3]. The platform's aims included providing up to three 15 kW devices with their ancillary power. These estimated power requirements for WECs to be connected were as shown in Table 1.

TABLE 1 [3]: LIST OF ANTICIPATED WEC ANCILLARY LOAD REQUIREMENTS

Ancillary loads	Power (W)
On-board PC	200
Industrial low power PC/PLC control system	50
Sensors	10
Camera	10
Telemetry	20
DC supply	30
Bilge Pumps	20
Nautical lighting	40
Miscellaneous	20
Total	400

Many of these loads require a constant supply of power and therefore the energy requirements of any on-board energy storage system becomes clearer. Other loads may include:

- Emergency lighting.
- Data acquisition.
- GPS tracker.
- Heaters, de humidifiers, fuel pumps may be required for some electrical equipment including any on-board diesel generator.
- Ventilation fans.
- Fire detection, prevention and fire-fighting services such as water spray system pump.
- Electrical equipment for watertight and fire-tight closing appliances.
- Alarms.
- Large circuit contactors and smaller relays operated from the PLC.
- PTO associated loads, e.g. motoring a Wells turbine from standstill to allow electrical generator power to be converted from the input pneumatic power across the turbine blades.

V. IDENTIFYING THE REQUIREMENTS OF ENERGY SOURCES ON OFFSHORE WECs AND TIDAL ENERGY DEVICES

The device developer may power these loads from different sources, and may isolate certain systems, but it is very important to understand and be aware of all energy storage systems on-board. As the renewable energy source is intermittent and being tested, other

sources of energy and power need to be considered and practical aspects compared.

To identify the need and requirements of an energy storage system for the offshore marine renewable energy (MRE) prototype, the following questions may help:

1. Is it feasible to rely on the power developed from the (MRE) prototype to power any electrical loads and/or energy storage system?
2. Is it crucial to power any MRE loads at all times, including during calm/slack conditions with no power input from the waves or tide?
3. Should other sources of renewable electrical energy be considered including photovoltaics, small scale wind turbines, keeping in mind costs, space, time, reliability required?
4. Is there an available grid connection or source of power available from a nearby device and if so what are the limits and specifications?
5. What voltages/currents are available from the generator on board the WEC?
6. If a diesel generator is required, what are the refuelling intervals, and are they feasible?

VI. ENERGY SOURCES SUMMARY

Off-the shelf energy storage systems are examined and a summary of initial results are given in Table 2.

To reasonably compare energy storage systems, available modules are mostly examined. These provide

useful power and energy values for developers. These modules include spacing between internal cells/batteries or capacitors, module housing, and sometimes internal electronics, which all decrease the energy and power densities as well as specific energies and powers compared to individual cells. Power density and specific power were evaluated using continuous rated power instead of peak values. Other assumptions include:

- Using name-plate capacity values for energy.
- Ignoring the Peukert effect, the depth of discharge, and charge/discharge efficiencies.
- *There was no value available on the datasheet for rated continuous power for the EX33 Module Li-ion capacitor.
- ** The sun | powerpack premium would be expected to have the same power density as the Nissan leaf battery, but the recommend power converter limits the available power.
- *** The lead acid batteries' rated continuous powers were based on the maximum charge current recommended in DIN 41773 (to not decrease the battery lifespan), which is 20 A per 100 Ah. This is equivalent to the C10 discharge rating, where the battery is discharged at constant current over 10 hours. In reality much larger charge/discharge powers are available and are determined based on the charger/load settings.

TABLE 2: COMPARISON OF ELECTRICAL ENERGY STORAGE TECHNOLOGIES

Product	Powerwall 2 Li-ion Battery [5]	Nissan Leaf Li-ion Battery [6]	BMOD0063 P125 Supercapacitor Module [8]	EX33 Module Li-ion Capacitor [9]	sun powerpack premium 30,0/48 Li-ion Bat. [10]	net.power 12V 170 x 24 Sealed Lead Acid Battery [11]	sun power VR M 12-150 Sealed Lead Acid Battery [12]
Manufacturer	Tesla	Nissan and NEC	Maxwell Technologies	EAS Elettronica JSR Micro N.V.	HOPPECKE	HOPPECKE	HOPPECKE
Mass (kg)	120	294	61	5.6	405	1548	55
Length (m)	1.15	1.5705	0.707	0.264	2.9	1.42	0.498
Width (m)	0.755	1.188	0.425	0.167	0.35	0.62	0.177
Height (m)	0.155	0.2649	0.274	0.155	0.6	2.12	0.23
Capacity (kWh)	13.5	24	0.103	0.053	30	45.53	1.81
Battery or Capacitor voltage (V)	50		125	45.6	51.2	48	12
Rated continuous power (kW)	5	80 [7]	14.6	17* peak power	7.5**	9.1***	0.36***
Energy density (Wh/L)	100	49	1.3	7.8	49.3	24.4	89.3
Specific energy (Wh/kg)	113	82	1.7	9.5	74.1	29.4	32.9
Power density (W/L)	37	162	177	2488	12	4.9	17.8
Specific power (W/kg)	42	272	239	3036	19	5.9	6.5
Cost per kWh (€/kWh)	490				980	190	180

Table 2 shows that supercapacitors have the lowest energy density, second lowest is the Li-ion capacitor, followed by the lead acid batteries, and the Li-ion batteries seem the most energy dense.

Flywheel values are similar to supercapacitors. As this paper is geared towards energy storage options, an initial comparison of the higher energy density technologies of lead acid and lithium ion batteries will be examined in more detail while the other high power technologies of supercapacitors and lithium-ion capacitors will not be explored further here. Flywheels and supercapacitors might be more suited for short term energy storage, peak shaving and power quality/system services applications.

The calorific value of diesel is 10.7 kWh/L, and 12.9 kWh/kg [14]. Diesel generators have an efficiency of about 28%. This gives values of 3 kWh/L and 3.6 kWh/kg, indicating diesel generators as effective energy storage choices as well as being an established and mature technology.

It is useful to compare technologies from the same manufacturer. These are the HOPPECKE products in Table 2. While the general differences between the lead acid batteries and the Li-ion battery will be presented in the following section. The net.power lead acid battery described was purchased for an offshore power platform [2], but this battery is designed as a reserve power system to be used infrequently, while the sun | power VR M battery is designed for a high cycle life, specifically for solar applications, with a cycle life of 7,000 cycles at 80% depth of discharge (DOD). Also, while the energy and power densities appear quite different for the net.power and sun | power lead acid batteries in Table 2, they are in reality very similar and the difference in the table arises from comparing a rack of net.power batteries with spacing and cabling and terminal connection points included, to a single sun | power battery.

VII. PRACTICAL CONSIDERATIONS ASSOCIATED WITH DIFFERENT ENERGY STORAGE SOLUTIONS

While comparing different energy storage solutions in terms of energy and power density as in Table 2, is useful as a first comparison, there are many other practical issues to consider associated with offshore MRE prototypes. These include

- Installation guidelines including ventilation.
- Operating procedures.
- Monitoring.
- Associated electrical equipment and cabling required e.g. converters, sensors, Battery Management Systems (BMS).

- Maintenance issues.
- Grounding.
- Electromagnetic Interference (EMI) of converters and component susceptibility to EMI.
- Environmental concerns.
- Safety.
- Reliability.
- Expected lifetime.

These all combine to give an indication of the overall cost associated with the system. This section will examine some of these issues associated with each of the available energy storage technologies.

A. Lead acid batteries

Types of lead acid battery include the Valve Regulated Lead Acid (VRLA) battery and the Absorbed Glass Mat (AGM) battery.

1) *VRLA battery*: The cell containers that make up the battery are sealed to prevent leakage and there is also a pressure relief non-return valve. This valve allows the safe escape of hydrogen and oxygen that are formed during charging [15]. As these gases are flammable, clearances and fire warnings are often provided.

2) *AGM battery*: In these sealed batteries the acid is absorbed between the positive and negative plates and immobilized by a fiberglass mat [15]. The AGM battery is a variant of the sealed VRLA battery.

The lead acid batteries in Table 2, the net.power 12V 170 and the sun | power VR M 12-150, are VRLA batteries using AGM technology. Some important considerations when installing, commissioning and operating VRLA batteries including AGM types, are specified in manuals like the HOPPECKE manual for VRLA stationary batteries [13]:

- Clear voltage risks that require insulated tools, removal of metal jewellery, wearing of insulating gloves and protective shoes.
- Risk of short circuiting and damaging the battery.
- Risk of contact with sulphuric acid if there are damaged cells.
- Risk of fire and explosion due to hydrogen and oxygen production, so keep sources of ignition away from terminals. On further inspection, hydrogen concentrations are recommended to remain below 2% per

volume, as explosive mixture occurs at 4%, and a good summary of this issue is given in [16]. The buoyancy and diffusivity of hydrogen make it unlikely that it will explode or be confined where asphyxiation may occur. To check ventilation equations, see standard EN 50272-2. Hydrogen is non-toxic.

- Other PPE required; protective goggles, face shield, face mask, rubber apron, fire extinguisher, and emergency eye wash.
- Ease of cable terminations with cable connectors, cables and terminal locations.
- Presence of lead requiring specific disposal.
- Sealed lead-acid battery to be placed in a stationary environment?
- Cells must not be refilled with water during the entire battery service life.
- Maintenance involving the voltage measurement of all batteries in the system every 6 months.
- Capacity taking into account the trade-off between depth of discharge (DOD) and cycle lifetime, and the Peukert effect where capacity is reduced for higher charge and discharge rates.

In close proximity to the battery, dilution of explosive gasses is not always given, therefore a safety distance has to be realised by a clearance in which there must be no sparking or ignition sources. The safety distance d can be calculated according to the formula stated in the standard EN 50272-2 (Safety requirements for secondary batteries and battery installations) [13]. The distance clearance d in mm, for a given number of cells n of capacity C , and where I is a value for the current producing gas in mA per Ah from Table 1 in EN50272-2, is shown in (1).

$$d=28.8 ({}^3\sqrt{n}) ({}^3\sqrt{I}) ({}^3\sqrt{C}) \quad (1)$$

Lead Acid Battery Advantages:

- Established technology.
- Minimum parts.
- Charging and discharging through a range of standard drives.
- Demonstration of operating in transport environment with high humidity, large vibration and movement, over a range of temperatures, over many years with many charge/discharge cycles, and able to provide large power.

Lead Acid Battery Disadvantages

- Heavy.
- Not as energy and power dense as lithium ion battery technology.
- Safety worry of hydrogen gas which requires clearances and ventilation. Though generally produced hydrogen will remain below flammable concentration and will rise and dissipate through walls and fittings. To check ventilation data equations, see standard EN 50272-2.

B. Lithium ion batteries

Installing, commissioning and operating lithium ion batteries, has some important considerations that are included in manuals like the Operating Manual for the HOPPECKE sun | powerpack premium [10].

- Operating above 80°C or operating defective batteries (e.g. sustained mechanical damage) includes the danger of the Li-ion batteries bursting and the discharge of liquid electrolyte and gases which are flammable. The electrolytes and electrodes may react with water and humidity. Coming into contact with the components of the battery may pose a serious health and environmental hazard. For these reasons adequate physical protection and ventilation must be provided.
- Specific instructions for users and specialists are given for damaged batteries which are a risk. E.g. Damaged batteries must be surrounded with dry sand, chalk powder (CaCO₃) or Vermiculite and if possible stored outside buildings.
- Smoke alarms are necessary at the installation location.
- It is recommended to store in a cool, frost free and dry place, and protect from exposure to sunlight, sources of radiation and heat sources. The sun | powerpack premium also requires the installation site to be vibration-free and not in rooms endangered by floods.
- The battery system should not be covered or concealed to dissipate waste heat optimally.
- Only approved battery inverters/battery chargers are suitable. These often operate in the range of hundreds of volts dc which has some safety and compatibility issues in comparison to lower and standard voltages.
- Special start-up sequences and interfaces are required to open contactors and operate the battery through its battery management system

(BMS) often with a Controller Area Network (CAN) data interface. Voltages and temperatures of individual battery cells are acquired through this system and associated cabling and is needed for trouble-free operation and management of the system.

- Two persons are required for the installation and subsequent disassembly with associated PPE.
- Completely discharging the battery may permanently damage it.

Lithium Ion Battery Advantages

- Most energy dense battery technology, and provides high powers.
- Lighter than lead acid batteries.
- Good cycle life parameters which suit solar photovoltaic charging profiles.
- Established technology becoming more popular in all applications and decreasing in cost.

Lithium Ion Battery Disadvantages

- Some recent heavy publicized failures where explosions and fires affected the development of prototypes (Samsung S7 note and Boeing 787 Dreamliner).
- Increased health and environment concerns compared to lead acid batteries, especially in a prototype MRE system which is at risk of sinking or internal compartments/spaces flooding.
- While Li-ion automotive batteries are becoming more popular these car batteries aren't interchangeable to prototype systems.
- Expensive.
- Special equipment and inverters required.

C. Diesel generators

Diesel generators in offshore marine applications are a proven and robust solution, an example of the device used in [2] is the Kubota Diesel Engine, Model: V1903-EBG, Rating: 16.4 kW. If placed offshore on a MRE device, remote operation of the generator and level sensor inputs to the on-board control system could inform the remote operators about upcoming maintenance requirements and diesel refilling schedules. Typical checks include:

- Oil and water levels or leaks.
- Coolant levels or leaks.
- Electrical functionality of glow and pilot lamps.

- Engine noise.
- Colour of exhaust fumes.
- Nuts and bolts tightness.
- Dust in air cleaner dust cup.
- Check fuel pipes and clamp bands.
- Battery electrolyte level.
- Check if there are obstacles around cooling air input or exhaust pipes.

The service intervals for the V1903-EBG Kubota engine range from 50 hours for basic checks, to two years for large replacement jobs such as battery, fuel pipes and clamp bands, intake air line, radiator coolant, radiator hoses and clamp bands swap out.

The estimates made earlier for specific energy and energy density values allow a clear comparison with battery technology.

Diesel Engine Generators Advantages

- Proven robust solution in offshore environment.
- Energy dense fuel.

Diesel Engine Generators Disadvantages

The motivations for avoiding diesel generators include:

- Pollution and environmental issues.
- Noise.
- Increased maintenance and system complexity.
- Refuelling – energy store must be replenished as used, there is no option to recharge the store without human intervention. Wind/PV battery systems offer autonomous operation.

VIII. ON-BOARD RENEWABLE ENERGY DEVICES

Including on-board solar panels and wind turbines to the offshore MRE devices may help to provide a low power source of energy that could extend maintenance intervals and provide much of the energy needs of the on-board electrical systems. The average raw power of sunshine per square metre of flat ground is roughly 100 W/m² in the UK, while PVs are about 10% to 20% efficient [10]. Although the power from these small scale devices would be low, they would act as backup sources.

Small scale wind turbines are available, for example the Superwind 350 [17], which can charge batteries at 12 V or 24 V. This is a 11.5 kg, 350 W rated permanent magnet device. Rated power occurs at 12 m/s upwards.

IX. CASE STUDY

A tidal energy company, GKinetic Energy Limited, were looking to build on their successful tidal prototype device testing in 2015 shown in Fig. 1.



Fig. 1: GKinetic's OC1 in Limerick, Ireland 2015

The energy requirements were:

- Ideally the turbine will not be shore connected and will not use an on-board generator.
- Moving the system to dockside once every 10 days could be tolerated for a period of a few months but would not be a long term solution.
- Everything will shut down except essential equipment when the machine is not generating sufficient power. Essential alarm systems are:
 - a) Anchor alarm: Triggered if the device moves off station, linked to both the GSM (Global System for Mobile communications) module and an on-board alarm strobe light. The GPS (Global Positioning System) would have sufficient capacity to switch power to the strobe without a relay.
 - b) Bilge pump alarm: Triggered when the bilge pump float switch is activated. The float switch is activated by air pressure and will have no current draw.

TABLE 3: BATTERY ENERGY LOAD REQUIREMENTS FOR GKINETIC TIDAL PROTOTYPE

Essential Services	Power (W)	Energy (Wh)
LED anchor light 16 hrs	2	32
GPS system	12	288
GSM module	15	360
Total over 10 days		6800
Essential Alarm Mode	Power (W)	Energy (Wh)
Bilge pump moving 15 L/min	130	3120
Strobe light	4	96
Total over 1 day		3216
Total energy required from ESS		10016

- These alarm systems would not add to the electrical draw until the alarms are activated. The bilge alarm would trigger an immediate response from support personnel and would demand a rapid intervention, probably within 24 hours.

Table 3 shows a summary of the energy load requirements for the GKinetic tidal prototype.

Batteries

To satisfy these energy requirements in Table 3, the sun | power VR M 12-150 sealed lead acid battery from Table 1 will be investigated. This battery is rated at 1.8 kWh using a 50-hour discharge rate. At 80% DOD and at 80% capacity at end of life, this would give 1.158 kWh. Assuming a 90% battery discharge efficiency and a 90% converter efficiency gives 0.94 kWh of usable storage per battery. Twelve of these batteries should give 11.26 kWh, at 80% DOD, at EOL, assuming 90% discharge efficiency, and 90% converter efficiency, based on the 50-hour discharge rate capacity. These batteries would be arranged in six parallel strings of two in series to give 24 V which is a usable voltage in the system. The approximate weight of these 12 batteries is 660 kg.

Solar PV and wind turbine

There is 1.5 x 3 metres of space for solar panels and also room for an on-board wind turbine.

Assuming 4 square metres of usable solar photovoltaics (PV), and assuming the complete conversion process of the average insolation incident on a horizontal surface (kWh/m²/day) for the location [17] to battery energy is 10% efficient. Choosing the worst case solar energy scenario December average of 0.5 kWh/m²/day and the best case, May average of 4.57 kWh/m²/day would produce 200 Wh and 1800 Wh for a 24-hour period accordingly.

For winter low insolation levels the PV system would not be able to keep up with the energy demands from the essential services without an additional energy source. From a simple monthly analysis, the PV system would provide adequate energy in a 24 hr period from March – September inclusive.

The average wind speed for Limerick is about 5.3 m/s. From the Superwind 350 wind turbine manual [18], this would result in about 1 kWh per day of energy, or about 42 W on average, which could also help satisfy most of the loads.

Due to weather unpredictability, installing both wind and solar options should provide enough energy while also providing system redundancy.

X. CONCLUSION

This paper examined and compared energy storage solutions for offshore Marine Renewable Energy (MRE) device prototypes. The motivations for different technologies and the design criteria were emphasised. Lead acid batteries, lithium ion batteries, and diesel and diesel generators were investigated. A focus was placed on operational and maintenance requirements to aid and highlight issues to device developers.

Due to factors like safety, cost, and complexity, it seems that lead acid batteries are better suited for early stage offshore MRE prototype developers than lithium ion battery technology.

A case study was presented on the energy balance, battery sizing and wind/solar renewable options for a small tidal turbine device.

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