Final Report: Wave Energy Converter from Repurposed Materials

Honours Thesis [1976]

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Declarations

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Originality

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Heinrich, T., Sebi, A., & Wicik, P.
Executive Summary

Every year there is an increasing demand for power around the world and a large proportion of this growth is in the developing world where an estimated 1.2 billion people live without reliable access to electricity. Electrification contributes to developmental outcomes in education, gender equality, health, and social and economic mobility. Renewable solutions are highly desirable due to low environmental impacts and low running costs; however the initial capital for these systems is often large.

Currently, some non-government organisations are working on solar and wind systems to charge batteries and provide electricity for resource-constrained communities. Research did not identify any organisations pursuing wave power for the same means and this project was an investigation into whether small-scale wave power systems can be used for rural electrification in the developing world. More specifically, the aim of this project was to create guidelines for the construction of wave energy converter systems from repurposed materials. This empowers rural communities to achieve small-scale electrification without a dependence on government or non-government organisations.

Current wave energy systems were researched and assessed based on their suitability for small-scale adaptation and construction from repurposed materials. As a dominant design for wave energy converters has yet to emerge, the literature of different prototypes in the testing and demonstration phase is broad. Several companies have invested tens of millions of dollars on systems with vastly different operating principles; however a design that converts low-frequency, erratic ocean waves into competitively priced and reliable electricity has yet to emerge out of the developmental phase.

No systems in the literature were considered suitable for direct down-scaling, but instead a clean slate design approach was taken. Four concepts were developed based upon three wave energy operating principles: two point absorbers, one oscillating water column and one tapered wave channel. The concepts were analysed for their constructability from repurposed materials and the potential power they could produce. The respective design concepts were evaluated, and the two point absorber concepts (linear generator buoy and bicycle point absorber) were considered most suitable for prototyping.

In order to replicate the construction resources of target communities, the prototypes were built from predominantly repurposed materials and outside of a workshop setting. At various stages in the construction the behaviour of individual subsystems and entire prototypes was trialled. The linear generator buoy concept was found to be an ineffective means of converting low frequency waves into usable power and so development of this prototype was discontinued. The mechanics of the bicycle point absorber prototype showed strong potential for successfully converting low frequency linear motion of a buoy into usable electricity. This was prioritised as the most effective solution to meet the aims of the project.
The bicycle point absorber was tested in laboratory and field settings. Testing in the School of Civil, Environmental and Mining Engineering’s wave flume revealed that the prototype behaved as designed and power was produced. Due to the limited range of conditions that could be simulated by the wave flume, the power output in this setting was insufficient to achieve the aim of charging a battery. Dimensionless scaling was considered but not deemed viable due to the difficulty in accurately scaling generator outputs and charging capacity. Meaningful data of the prototype’s performance was collected at Brighton Beach, South Australia. In real wave conditions, it was initially found that power production was too erratic to produce useful electricity and charge a battery. In order to address this issue, the mechanical inertia of the system was increased by adding weight to the drive wheel, and a smoothing capacitor was introduced to the electrical system.

Field testing results showed that for waves of up to 0.70m in height, 3-5W was produced when connected to a direct load of 200Ω. A charging circuit was incorporated in order to convert the electrical output into a form suitable for charging a 12V battery. It was observed that 0.70m was the approximate start-up wave height for the prototype to charge a battery. This shows that small-scale wave energy from repurposed materials can be a viable option for providing minimum power requirements to a rural community.

Guidelines have been developed that provide suggestions for producing a bicycle point absorber system. These contain explanations of the roles of different subsystems, how they were produced in the prototype and lessons learned. These guidelines have been made available to non-government organisations that operate in coastal regions with low electrification rates. The guidelines may also be made available as a teaching resource for secondary schools to promote interest in science, engineering and humanitarian projects.
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Chapter 1

Introduction

Worldwide, an estimated 1.2 billion people live without reliable access to electricity [1]. The introduction of electricity to a community has been proven to improve outcomes in education [2], gender equality [2], health [3], and social and economic mobility [4]. Evidence suggests that technological humanitarian intervention projects can be successful if they are designed from parts available in the client’s community [5]. This avoids the common pitfall of advanced engineering solutions that cannot be independently maintained by the community themselves [6]. Therefore, with adequate information and management, areas lacking in access to reliable electricity have the opportunity to benefit greatly from alternative power generation systems.

The electrification of rural communities whose location makes connecting to major electricity grids prohibitively expensive is identified by several non-government organisations (NGOs) as a priority. For example in Peru, the NGO Soluciones Practicas is responsible for installing wind turbines in remote Andean communities [7]. Follow-up work on these projects has shown the long-term social change produced, with many households using electric lighting in the evening to study, [8] and produce woven and knitted goods. Similarly, the NGO blueEnergy has been involved in programs in rural Nicaragua, working in coastal regions lacking in land access, and 80% of the population does not have access to electricity [9]. In the period 2008-2010, many of blueEnergy’s installations were disassembled and removed after varying in-field success [10]. Major issues included poor wind resources, lightning strikes, preoccupation of inter-community territorial conflict, and harsh environmental conditions. [10]. However, the pressing need for electrification remains and these studies highlight that work must continue advancing even with current limitations.

In planning the electrification of rural communities, the cost of extending pre-existing grid networks to these locations must be compared against the cost of installing a new micro-grid and power source. For communities where the installation of a micro-grid is more economically viable than connection to a major regional electricity grid, a decision must then be made between cheap fossil fuel based supplies i.e. diesel generators, and renewable energy technologies. Although diesel generators are a proven technology with low capital cost, the price of diesel fuel is increasing [11]. Additionally, the ongoing procurement of fuel requires resources that could otherwise be used more productively. In comparison, renewable energy technologies have fewer on-going costs, and although they are initially more expensive, prices are rapidly decreasing with technological development [12].

There are three key criteria that make off-grid renewable energy solutions well suited to a community. Firstly, the location of the community make connection to a major elec-
tricity grid prohibitively expensive [13]. Additionally, the resource outlay in procuring fuel for a traditional combustion generator is considerable [13]. Finally, energy sources must be available that make the financial outlay for a renewable energy system viable. Successful off-grid power generation systems are matched to their operating environment.

In 2014, a mechanical engineering honours team at the University of Adelaide created guidelines for the construction of wind turbines from repurposed materials. The designs were flexible and could be altered for different conditions and constructed using various components. In wind tunnel testing, a horizontal axis wind turbine using a treadmill motor achieved a roughly linear power output ranging 0-5W for wind speeds of 3.5-7.5m/s and a nominal load of 20Ω [14]. A second horizontal axis wind turbine using a washing machine motor achieved a power output ranging from 43-187W for wind speeds of 6-10m/s [14]. The washing machine motor used was ideally suited for being repurposed as a generator, but is a specific model and does not represent a general solution for creating electricity from scrap materials.

In 2015, two teams at the University of Adelaide have expanded on the renewable energy from repurposed materials concept. One team has explored hydroelectric systems, and this report is focused on wave energy converters. By having many different small scale renewable energy systems, more communities will be able to harness the energy available to them within their immediate environment.

In the course of this project a small scale wave energy converter (WEC) prototype was designed and constructed. Based upon this experience guidelines for adaptable WEC construction capable of providing minimum community power requirements were written. The WEC design guidelines are adaptable enough so that communities who have access to different terrains and materials can adjust the system for their own requirements. The guidelines also include detailed step-by-step instructions for less flexible parts of the design. To come to this conclusion, the project reverse engineered several contemporary WECs in order to design and build a prototype as proof of concept. The final prototype has been constructed using scrap materials and with only basic machining to represent the communities’ ability to construct a similar system.

1.1 Literature Review

Due to the codependency of quality of life and energy consumption, approximately 75% of the world’s energy is consumed by the richest 25% of the world’s population [15]. Expanding access to electricity in the developing world will be a key contributor to increasing the quality of life in developing countries [1] and is therefore the focus of current work.

With approximately 82.5% of the world’s population in developing countries [4], there will be an estimated 56% increase in energy consumption from 2013 levels by 2040 [16]; this is shown in Figure 1.1, which projects the total energy consumption for both member and non-member countries of the Organisation for Economic Co-operation and Development (OECD) as well as the energy consumption by fuel [16]. Growth will be dominated by countries that are not currently a part of the OECD. By creating innovative methods for expanding access to electricity in the developing world, the project aided the achievement of key development outcomes.
Electrification of communities reduces the need for alternative forms of lighting such as oil lamps, improving indoor air quality and reducing respiratory health problems [17]. In theory, the same outcome is true for cooking equipment; however, in practice the investment cost in new appliances is often too great [17]. Similarly, rural community electrification increases access to media through television, radio and internet [17]. This has multiple benefits including, but not limited to, educational programming for adults and children, engagement with news and current affairs, building political awareness and improved health knowledge (including family planning) [17]. A case study in Madagascar identified that electrification of communities was shown to improve educational outcomes by enabling students to study after sunset [2]. Similar results have been reported in other studies by Mulder and Tembe (2008), and Saghir (2005). Research also supported the hypothesis that electrification aids gender equality as females are more often expected to do housework after school. Lighting from a reliable source of electricity then allows them better opportunity to study in the evening [2]. With an ever increasing demand for energy on a global scale, there is a large market for all energy production systems, however a focus on small scale renewable energies systems will be best suited for off the grid communities. If these small scale systems can be designed and built from repurposed or available low cost materials then remote communities can create these systems to have a constant reliable and renewable supply of energy.

1.1.1 Renewable Energy Sources

By the end of 2013 an estimated 22.1% of global energy production came from renewable sources. By percentage contribution in descending order these forms of renewable energies are hydropower, wind, bio-fuels, solar, geothermal and wave power [20]. Each of these forms of renewable energy bring individual advantages and disadvantages.

1.1.1.1 Hydropower

Hydropower is currently the most commonly used form of renewable energy production with usage in over 100 countries [21]. Hydropower creates energy by using flowing or falling water, a change in potential energy, to provide work for a turbine. This form of energy production is only possible in locations with dams or moving water such as a river. The advantages of this system are that it is a simple, proven technology, emits
no pollution and has an extremely low operating cost [22]. It is applicable technology for smaller communities as the system size easily adapted to suit any small scale requirements. Most hydropower systems have a large initial capital expenditure and if it relies on a dam then significant land area is necessary, which has a large micro environmental effect [21]. However if the system is designed to work on a small-scale by flowing water way then these disadvantages can be managed. As a result, there is currently an honours project in progress at the University of Adelaide looking into applying this technology for humanitarian use.

1.1.1.2 Wind

A wind turbine can produce energy from the kinetic energy of the wind turning the turbine. Many areas of the world have wind resources and therefore this form of renewable energy can be widely applied. The system also has the advantage of being a reasonably simple proven technology which has very low running costs [23]. Without a battery storage system or constant supply of wind, this form of energy production cannot solely supply regular energy to a community [21]. A small scale system would have a much smaller initial capital cost, particularly when built from scrap materials and The University of Adelaide has a completed 2014 honours project that researched and developed this technology from scrap material for use in remote communities.

1.1.1.3 Bio-Fuels and Bio-Mass

Bio-fuels work in a similar way to fossil fuels, where combusted thermal energy is converted by the system into useful electricity [24]. Bio-fuels are considered a form of renewable energy as they are carbon neutral, achieved by having the same amount of fuel growing around the world as is used in energy production, therefore the emissions from the system are absorbed by growing plants. There are however, issues for the growth, transportation, processing of the life matter and short term air pollution [21] make bio-fuels inappropriate for small-scale renewable electrification. Furthermore, food commodities and croplands are diverted towards the production of biofuels and can threaten global food supply [25].

1.1.1.4 Solar

Solar systems use either photovoltaic or solar-thermal technologies to convert radiant light and heat respectively from sun exposure into useful energy such as electricity or as a heating system [21]. Solar systems are reliable during daylight hours, especially during summer periods, and also have very low running costs. Solar systems can be used almost anywhere in the world, with locations that receive large solar radiance being preferable [26]. The drawbacks for this technology include the large initial capital expenditure and the fact that no energy is produced at night. This form of technology is less a viable solution for remote communities with limited access to solar panels as they are an expensive and specialised technology that needs to be externally sourced.

1.1.1.5 Geothermal

Geothermal energy conversion uses the heat contained under the Earth’s surface to work a conventional power plant by heating a working fluid to turn a turbine. These systems must be quite large and have a very limited number of available locations for power generation. Deep wells must be drilled into the ground to utilise this energy source [27] and therefore
this system is not a viable option to be created as a small scale energy production system from repurposed material.

1.1.1.6 Wave

The movement of waves and the currents in the seas around the world can be used in many different ways to create energy by using the kinetic energy of the waves to produce power. One of the largest benefits of ocean power systems is that they can produce electricity 24 hours a day [28]. The largest drawbacks of ocean systems are the limitation to coastal areas with relatively large waves, high initial capital expenditure and the corrosive environment. The principles of existing wave energy systems are detailed in Section 1.2.

1.2 Wave Energy Converter Systems

Several types of wave energy converters (WECs) have been developed, however a dominant design has yet to be established. The reason for this is due to the fact that there are many different methods of converting the kinetic energy in ocean waves into useful electricity. The power in a wave depends largely on the amplitude and frequency as shown below in Equation 1.1.

\[ P_w = \frac{\rho g^2 T A^2}{8\pi} \] (1.1)

where \( P_w \) is the power per unit length (W/m), \( \rho \) is the density of water (kg/m\(^3\)), \( g \) is gravitational acceleration (m/s\(^2\)), \( T \) is the wave period (s) and \( A \) is the wave amplitude (m). Most current WECs are of an industrial size, with rated power outputs from 50kW-1MW (Subsections 1.2.1-1.2.4). No evidence has been found for small-scale WECs that have been developed to provide domestic requirements for isolated communities.

1.2.1 Oscillating Water Columns

Oscillating water column (OWC) WEC systems use the motion of waves to displace air in a closed volume to operate a turbine. Air is forced in and out of the volume with the motion of the waves. A turbine is located in front of the opening, and so the air becomes the working fluid in the power generation. As the water oscillates, a Wells turbine, in Figure 1.2 is often used as it is independent of rotation direction, allowing airflow to be bidirectional [29].

This concept is used in the Islay LIMPET system in Scotland which opened in 2000 and is rated at 250kW [30]. A large scale system such as the Islay LIMPET system requires a large initial capital expenditure for construction. There are many issues with converting this system to a small scale system made from scrap material. A large portion of the system needs to be submerged in the sea water, requiring advanced anti-corrosion measures or a concrete structure and both solutions are less practical for remote community construction. Therefore it is unlikely that this system will have guidelines developed for its construction.
1.2.2 Attenuator Systems

Attenuator WEC systems are snaking structures comprised of rigid cylindrical segments hinged together in series. Within these hinges are hydraulic rams and the motion of the waves causes the hinges to swing, activating the rams pumping oil through turbines \[29\]. The 2008 Pelamis project in Agucadoura, Portugal was comprised of 3 four-capsule attenuator systems, which together generate 2.25 MW as seen in Figure 1.3 and ran for two months before technical difficulties arose \[32\]. As this system requires more advanced material and construction, such as the involvement of hydraulic rams and complete waterproofing, it is not an applicable design for repurposed material construction.
1.2.3 Tapered Channel Devices

Tapered channel devices artificially focus waves through a funnel to increase wave height. The waves then enter an at-sea reservoir such that the water level inside the reservoir is greater than outside and water is allowed to flow through low-head hydro generators to convert the potential energy into electricity. In these cases, the turbines are often actively controlled to smooth out the generated power as a result of the natural fluctuations in the waves [29]. An example of a tapered channel device is the “Wave Dragon”, designed by the company of the same name which is a floating offshore converter without any moving parts apart from the power take off. In 2003 a prototype with seven turbines, each rated at 20kW was deployed and in 2004 the Wave Dragon delivered power to the grid until 2005 but was damaged [29] and currently further prototypes are being planned of various sizes up to 50MW. An ocean floating reservoir may not be sturdy enough to be designed from repurposed materials but the concept may be altered to provide a viable solution.

1.2.4 Point Absorbers

Point absorber WEC systems harness the oscillating motion of a buoy due to wave movements with the buoy typically cabled to a device on the ocean floor. This can be a generator or a hydraulic device that transmits the energy to land. Typically, point absorbers have small dimensions relative to wavelength and due to their size, wave direction is unimportant [28]. Therefore, buoys can be regarded as a single degree of freedom system. This means that the response is limited to vertical motion, referred to as a heaving motion, and that due to the small size of buoys, scattered and radiated waves become negligible [34]. As a result, the dynamics of buoys are simpler and have the advantage of being a more mobile system.

Point absorbers can be difficult to implement in reality with limited funding and technology as they require an intricate and often, underwater generator which can be housed within the buoy or externally with either requiring a high level of waterproofing. An investigation in to the sizing of buoy point absorbers was made by Garnaud and Mei (2010) which looked into whether it is more effective to use a compact array of small buoys or a large buoy. Their analytical results identified that a compact array would be more efficient in natural seas due to the higher degrees of freedom resulting in a broader bandwidth of high efficiency [35].

Typically, the generator is implemented within the buoy and can be in the form of a rotational, or linear generator (Figure 1.4). If a rotational generator is used then there must be some means of translating the vertical heaving motion of the buoy into rotational motion to generate electricity by using a rack and pinion or other such device [36]. Linear generators are attractive due to their mechanical simplicity and involve a translator upon which magnets are mounted. These magnets have alternating polarity and are directly coupled to the heaving buoy with the stator containing the windings and are mounted to a stationary structure such as the housing [28]. As an example, Foster (2011) developed and modelled such buoys using general calculations from the work of Garnaud and Mei (2010) to create a three-part system of surface buoy, power-take-off unit and tension buoy. The results simulated up to 2.24kW power extraction with wave data from Oahu in Hawaii. These studies validate various methods for power generation when using a buoy WEC system and imply that a certain degree of creativity is involved for implementation.
Chapter 1 Introduction

Figure 1.4: Example of a linear generator direct drive point absorber [37].

Research by Brown, Hardisty, and Molteno (2007) displays the feasibility of such a small-scale linear generation system for ocean exploration. It is an inertial power generation system included within an autonomous underwater glider (AUG) that operates as a buoy when on the surface of the water. Their requirement was for an output power of 10W whereupon the AUG would be recharged after 90 minutes and the low frequency, high energy waves highlighted the need for robust rectifier and regulatory circuitry. Typical large commercial point absorber systems deal with the dynamic wave range by using an intermediate, controllable power transfer stage to provide a constant speed drive for a generator. As this system was on a smaller scale, an alternative solution had to be found and a pulse width modulation controller was used. In order to fit their generator within the small AUG, an inertially coupled oscillating mass was used to extract wave energy [38]. Springs were then used in conjunction with a recirculating ball screw to convert linear to rotary motion. A DC generator was used and had a maximum continuous output of 22W with a peak output of 11.7V [38].

Another example of a buoy energy capture system is the PowerBuoy, developed by Ocean Power Technologies (OPT) that has been successfully tested off the coast of Scotland [39]. The PowerBuoy in Figure 1.5 operates with three sub-assemblies, where the float moves by wave action and the heave plate maintains the spar in a mostly stationary position. The method of electricity conversion in this case is by means of a direct drive generator where the vertical heave motion is converted to rotary motion using a rack and pinion mechanical system. The power is then delivered to a local payload or to the grid [39]. Currently, there are two iterations of the PowerBuoy, the APB-350, which is designed for 24/7 supply of lower 350W to 500W power and the PB40 designed for the utility industry and moderate-power payloads or a 40kW average power output [40]. This example shows the use of a rotational generator where heaving motion is translated to rotational motion mechanically within the buoy.
Eco Wave Power have developed a system that is capable of producing up to 5kW \cite{41}. As an array, the system (Figure 1.6) has a series of pontoons that are pushed up by incoming waves, these pontoons work hydraulic levers which in turn are used to generate power. Two different models have been created with the greatest benefits being a 30 year lifespan and a storm protection system in place.
1.3 Summary

As is shown from current solutions implemented around the world, there is a lack of small-scale WEC systems. One of the largest drawbacks to renewable energy systems is the initial large capital cost. Therefore the aim of the project was to provide guidelines and empower communities to build a low cost WEC. There were three main objectives to successfully meet the aim. These are further detailed in Appendix B.1.

1. Create a WEC system that can generate enough power to charge a typical mobile phone or automotive battery. This level of power generation is a realistic expectation for a system that uses mostly repurposed materials and the success will be qualified after the final prototypes are completed and experiments are conducted.

2. Test constructed final designs as proof of concept. All data will need to be obtained by the end of September to allow for processing and report writing time. The design will chiefly be tested infield to prove the concept charges a battery with sufficient wave sizes.

3. Write an adaptable set of guidelines that allow for construction with a variety of repurposed materials. Suggestions for diverse materials and methods of construction will need to be included in the guidelines to provide the desired variability. Realistically the degree to which subsystems can be altered will change depending on the technicality, therefore the drive system may be more flexible than the power generation system.

There are further objectives for the project to improve design functionality and to meet the overall humanitarian aims.

1. Create a system that is self-adjusting to work during high and low tides.

2. Create a system that is resistant to damage by corrosion. The system will be exposed to salty water and air conditions as well as a humid environment. Creating a system that can be shielded from outside conditions or easily maintained is preferable.

3. Create a system that can be built without a workshop or significant engineering knowledge. This expands the number of communities capable of constructing their own system.
Chapter 2

Electrical and Electronic Specifications

Although ocean waves typically have high power densities, a major obstacle in the development of WECs is harnessing this energy in a form suitable for electrical power generation. Wave energy varies substantially with respect to energy fluxes from deep to shallow and near to off-shore environments. Therefore, the associated electrical systems must be developed to cope with this wide range, or be specialised for certain conditions. As an example, long period waves of \(7 - 10 \text{ s}\) with a large amplitude (\(\sim 2\text{ m}\)) have energy fluxes on average between 40 and 70 kW/m \([43]\). The difficulties of harnessing wave energy have been concisely summarised by Clément et al. (2002):

- Irregularity in wave amplitude, phase and direction; it is difficult to obtain maximum efficiency of a device over the entire range of excitation frequencies
- The structural loading in the event of extreme weather conditions, such as hurricanes, may be as high as 100 times the average loading
- The coupling of the irregular, slow motion (frequency \(\geq 0.1\text{ Hz}\)) of a wave to electrical generators requires typically \(\sim 500\) times greater frequency.

Therefore, a trade-off must be made when designing WEC systems between efficiency, reliability, and economic feasibility.

While the energy conversion from wave to device varies substantially (see Section 1.2), methods for electrical power generation converge due to the low frequency of wave oscillations. Generally, conventional high speed rotary electrical generators are used such as induction or synchronous machines \([44]\). A large issue to overcome is the transfer of the low frequency oscillations to a faster rotational output. This can be achieved with gearing, hydraulics or by using a linear induction generator. The LIMPET OWC solution suffers due to the cost and efficiency change with the speed of the turbine, while hydraulic systems suffer from the need for highly effective sealing and the potential risk of oil leaks \([44]\). As the devices will be made from repurposed material where possible, sources of the largest efficiency losses must be targeted. One solution is to reduce the number of energy transfers by minimising moving parts. A variety of generators were investigated to identify the most suitable types for WECs.

2.1 Direct-Current Generators

Direct current (DC) flows in only one direction and is required to charge domestic batteries. In contrast, the voltage obtained from mains power supply or the grid is alternating current
meaning the voltage flows in a sinusoidal manner between positive and negative. To convert from alternating to direct current, the output must be rectified which can be achieved with the use of diodes as explained in Section 2.5. DC motors and generators are typically built the same way and can often be used interchangeably. The voltage output of DC generators is alternating current (AC) but is rectified by the commutator within the DC machine. The generation of voltage arises as a result of the rotation of the coil between the North and South poles of a permanent magnet or vice versa. Figure 2.1 shows a DC generator with commutator and voltage output plot.

2.2 Polyphase Circuits

Polyphase circuits are systems which carry three or more phases of alternating current at defined time intervals. For example, by taking the sum all phases in a three-phase system, the total power is 1.5 times greater than an equivalent single phase system [46]. When looking at phase circuits it is useful to consider the analogy of cylinders in an engine. The cylinders move in unison but are staggered such that the power is delivered in a pulsed manner. These pulses correspond to the frequency of the power and result in a more consistent power output. Figure 2.2 shows the sinusoidal voltage outputs of three phase power. A synchronous generator produces power at a frequency corresponding to the speed of the rotor. Here, the rotating magnetic fields of both rotor and stator are locked. Typical polyphase machines are wound rotor synchronous (e.g. car alternator) or squirrel cage induction machines.
2.2 Polyphase Circuits

Induction machines consist of two major parts: a stator and a rotor. When supplied with three phase power, it produces a synchronous rotating magnetic field and acts as a motor. If the rotor is worked faster than synchronous speed, then the machine will function as a generator.

There are two main types of induction machines, the first being *squirrel-cage* and the second being *wound-rotor*. The rotor of a squirrel cage machine can be seen in Figure 2.3. Squirrel cage rotors allow higher operation speeds but have the drawback of requiring external power to excite and magnetise the generator. If not connected to another external power source, large capacitors can be used in parallel to provide the reactive power. Wound rotor induction machines have 3-phase windings on the stator and are each connected to slip-rings that turn with the rotor.

Considerations for the use of induction generators with WEC systems are outlined in a study by Indiresan and Murthy (1989). As a constant reactive power is required for non-permanent magnet generators, they are less suitable for the purposes of the project. Permanent magnet induction generators may be possible but are rare given the cost of powerful permanent magnets and efficiency of reactive power induction machines.
2.3 Stepper Motors

Stepper motors are special motors used when precision is required and as the name implies, their motion is carried out in steps according to the structure of the stator and rotor. There are three main types of stepper motors being:

- variable reluctance (VR),
- permanent magnet (PM), and
- hybrid.

These motors are explained in further detail by Wildi (2006) but in summary, variable reluctance stepper motors use a soft iron rotor and electromagnetic stator while both PM and hybrid stepper motors have permanent magnet rotors. Figure 2.4 shows the operation of an elementary PM stepper motor which makes it clear to see that the rotor will lock against the previously excited stator poles when no current flows in the stator windings.

![PM stepper motor with half step motion](image)

Figure 2.4: PM stepper motor with half step motion [50].

If an external torque is applied to a PM or hybrid stepper motor, a respective phased current could be induced and therefore it would act as a generator. As variable reluctance stepper motors use a soft iron core, providing an external torque would not create any magnetic field and therefore would not act as a generator.
2.4 Linear Induction Machine

Linear induction machines use an unrolled stator and rotor to couple linear motion to a change in electromagnetic flux as opposed to rotational motion. In the case of a generator, a current is induced by moving a conductor across a magnetic field or vice versa. Renewable energy systems such as WECs can use wave motion to move a magnet across a solenoid to produce useful electricity.

This process is mathematically described by Faraday’s law of induction which is shown in Equation 2.1:

$$\varepsilon = -N \frac{d\Phi}{dt}$$  \hspace{1cm} (2.1)

where $\varepsilon$ is the electromotive force (emf) (V), $N$ is the number of turns of the coil and $\Phi$ is the magnetic flux (T), which is dependent on both the magnitude of the magnetic field and the size of the surface affected.

The equation shows that if the flux linking a loop varies over time, a voltage is induced which is proportional to the rate of change of flux. Furthermore as the magnetic field strength is inversely proportional to the distance between the magnet and coil; having the solenoid as close to the magnet as possible is more conducive to power generation. As an alternating current would be produced from oscillating wave motion, this type of generator would require rectification to be a viable option for battery charging.

2.5 Rectification

Rectifiers are electronic devices that convert AC to DC. These can be single phase or multi-phase and are necessary for AC generating WECs in order to charge a battery. Single phase rectifiers are used to power most domestic items and multi-phase rectifiers are used to power industrial applications or transmit energy as DC. There are many rectification circuits all of which can be split into two groups, half wave and full wave rectification. Typically, the voltage drop of a small silicon diode is 0.7V but Schottky diodes can be used to reduce this voltage drop to 0.15V.

2.5.1 Half Wave Rectifier

Half wave rectification allows for half of an AC waveform to pass through the system and blocks the complementary half wave. The largest advantage of this rectifier type is its simple circuit design and the use of only one diode. The disadvantage of half wave rectifiers is that they reduce the total voltage output and effectively discarding the complementary waveform. This method produces a unidirectional pulsating DC which is undesirable as the peak to peak voltage is halved. Figure 2.5 displays the basic circuit design which includes the use of a capacitor to smooth the unidirectional pulsating DC.
2.5.2 Full Wave Rectifier

Full wave rectifiers convert AC into DC by allowing half of the waveform to pass through the diode bridge and then switching the polarity of the second half of the waveform. These rectifiers have the advantage of producing DC with a higher voltage output and reduced pulsating effect compared to half wave rectifiers. A general circuit requires four diodes in a bridge configuration. When this is coupled with a smoothing capacitor it provides a reasonably constant DC output from an AC input. Figure 2.6 shows the basic single phase circuit design and should be used instead of half wave rectification to best use the input current. The same principles apply for three-phase rectification but an alternative circuit must be used with the addition of two diodes.
2.6 Charge Controller

If an electric motor is to be repurposed as a generator to charge a battery, current must not flow from the battery to the motor, otherwise it will power the motor and turn the system. It must also ensure that the voltage generated does not become high enough to overcharge the battery. To address these issues a charge controller can be implemented which would contain a full wave rectifier circuit and a switching mechanism. This would change the load from the battery to a dump load when the battery is fully charged, or when the voltage is too high to safely charge the battery. Another solution to prevent overcharging would be to simply reduce or limit the voltage by using a regulator or transformer.

A basic charge controller circuit developed for solar or wind systems by Davis (2011) [54] is ideal as it is designed to ensure that the components needed are accessible to people in remote areas of the world. A table of the components required is listed in Table 2.1.

<table>
<thead>
<tr>
<th>Charge Controller Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC1 - 7805 5 Volt Voltage Regulator</td>
</tr>
<tr>
<td>IC2 - NE555 Timer Chip</td>
</tr>
<tr>
<td>PB1, PB2</td>
</tr>
<tr>
<td>LED1 - Green LED</td>
</tr>
<tr>
<td>LED2 - Yellow LED</td>
</tr>
<tr>
<td>RLY1 - 40 Amp SPDT Automotive Relay</td>
</tr>
<tr>
<td>D1 - 1N4001 or similar</td>
</tr>
<tr>
<td>R1, R2 - 10K Multi-Turn Trim-Pots</td>
</tr>
</tbody>
</table>

Importantly, there is an automotive relay to switch from the battery to the dump load, trimpots to tune the voltage range to adequately charge a 12V car battery, and an NE555 integrated circuit chip which are widely available. Note that this circuit is as stated for a 12V battery and an alternative or modified circuit must be used to charge a different sized battery such as for a smartphone.

2.7 Battery Types and Community Power Requirements

In order to create guidelines for WEC construction that will be useful for a community, the required power output must first be established. The goal of the WEC system is to provide the community with “minimum power requirements”. As more people have access to mobile phones than toilets [55], the ability of the WEC to charge phones will be an important aspect of the guidelines. Further increases in power production will add to the appeal of the guidelines and may provide for community lighting, whose associated benefits are highlighted in Section 1.1.

To determine the power requirements of a community lighting system, the activities of an existing rural electrification project are examined. The NGO “LED Africa” uses solar photovoltaic systems and battery storage to provide electricity to schools in rural Malawi, enabling students to study at night (Figure 2.7). Their lantern designs contain 48 LED globes, consume 5 Watts, and provide light for six students to study comfortably for 3
hours a night. For a 12V battery, these specifications result in 1.25 A h which is roughly \( \frac{1}{50} \)th the capacity of a regular car battery (see Appendix A.1).

![Figure 2.7: LED Africa lantern [56].](image)

Community requirements and potential charging times for battery types are important determining factors in WEC type selection. Table 2.2 shows battery capacity in Watt-hours and charging voltages for a range of batteries that can be found in the developing world. In practice, batteries charge over a small range of voltages and to charge a battery, an input voltage greater than the rated battery voltage is required. Furthermore, if the voltage input is too high, the battery may overcharge and become permanently damaged. The values listed in Table 2.2 are only a guide.

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Charging Voltage (V)</th>
<th>Capacity (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Car</td>
<td>13.8</td>
<td>840</td>
</tr>
<tr>
<td>Scooter/Motorcycle</td>
<td>7.0</td>
<td>12</td>
</tr>
<tr>
<td>Smartphone</td>
<td>4.2</td>
<td>5.25</td>
</tr>
<tr>
<td>Low-cost mobile phone</td>
<td>4.2</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Car batteries have the advantage of a large capacity, however their greater charging voltage is an extra requirement that must be considered in the WEC design. Scooters and motorcycles are especially popular in the developing world due to their lower price when compared with cars. To overcome their smaller capacity, several batteries could be connected in parallel. Specifications of batteries for smartphones and low-cost, basic phones are included due to their popularity in the developing world. A design concept’s ability to achieve charging voltage and charge the batteries mentioned within a satisfactory time-frame is a key factor in its feasibility assessment.
2.8 Summary

Considering the aforementioned, it is clear that for the purposes of a low power and low cost system that does not require reactive power, permanent magnet solutions are most suitable. A generator that requires reactive power from the battery to magnetise the windings may be a solution, but requires a high output power to sustain running as a generator. Sourcing permanent magnet machines with rare earth magnets is an issue as they are expensive compared to the other components of the system that can be readily sourced from scrap. Alternatively, rare earth magnets could be purchased and installed in an induction motor. A summary of generator suitability is listed below in Table 2.3.

<table>
<thead>
<tr>
<th>Generator Type</th>
<th>Permanent Magnets</th>
<th>Current</th>
<th>Scrap Availability</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Motor</td>
<td>Yes</td>
<td>DC</td>
<td>Yes</td>
<td>✓</td>
</tr>
<tr>
<td>Squirrel Cage Motor</td>
<td>No</td>
<td>AC</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Wound Motor</td>
<td>No</td>
<td>AC</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>PM Synchronous Motor</td>
<td>Yes</td>
<td>AC</td>
<td>No</td>
<td>✓</td>
</tr>
<tr>
<td>Linear Induction</td>
<td>Yes</td>
<td>AC</td>
<td>Yes</td>
<td>✓</td>
</tr>
<tr>
<td>VR Stepper Motor</td>
<td>No</td>
<td>AC</td>
<td>Unsure</td>
<td></td>
</tr>
<tr>
<td>PM Stepper Motor</td>
<td>Yes</td>
<td>AC</td>
<td>Rare</td>
<td>✓</td>
</tr>
<tr>
<td>Hybrid Stepper Motor</td>
<td>Yes</td>
<td>AC</td>
<td>Unsure</td>
<td>✓</td>
</tr>
</tbody>
</table>

If an AC generator is to be used, the current must be converted to DC in order to charge the batteries described in Section 2.7. To make the most of the power generated by the WEC, a full wave rectifier and smoothing capacitor should be used to produce a useful charging voltage as detailed in Subsection 2.5.2. As batteries can be overcharged and damaged, a charge controller is necessary. Once the battery has reached its maximum charge level, the power supply is switched to a dump load. Such a charge controller must be simple to construct with easily sourced components and a suitable design is described in Section 2.6.
Chapter 3

Concept Solutions and Analysis

In order to develop design concepts, the WEC systems described in Section 1.2 were analysed and the potential to adapt their operating principles considered. Small-scale and potentially low cost designs were developed incorporating the principles of:

- oscillating water columns,
- point absorbers, and
- tapered wave channels.

Materials listed in the design concepts are only suggestions and can be replaced with alternatives.

3.1 Oscillating Water Column

As described in Subsection 1.2.1, OWCs operate by using the varying water height inherent in ocean wave behaviour to force air in and out of a partially enclosed volume. The power output of OWCs is dependent on wave conditions and aspects of the design including the footprint and turbine system. An optimised OWC has a chimney that is small enough to force the air to flow at a fast rate to maximise kinetic energy and large enough to minimise back-pressure inefficiencies.

The chimney-turbine system of the basic OWC in Figure 3.1 could be constructed from sections of PET bottles or PVC pipes, and a turbine. Three variations of this OWC design were developed with different body designs:

- A small, mobile design that can be manually moved for changing tidal conditions;
- A larger, immobile design that produces considerably more power but cannot be adjusted for tides;
- A small, mobile design that runs on tracks and automatically adjusts for tidal conditions.

3.1.1 Design Concept 1: Mobile OWC

Design Concept 1 is a light-weight box OWC. The box could be made from treated wood or any other waterproof and sturdy material. In order to operate through changing tidal conditions, Design Concept 1 would need to be manually relocated. This limits the weight and size of the system, and hence output power. Alternatively, the system could be left near the high tide mark. In this scenario, power would only be produced for a fraction
of the day. The system would require an easy securing mechanism to stop it from being moved by the waves. The biggest advantage of this system is that due to its simplicity, it could be constructed rapidly.

### 3.1.2 Design Concept 2: Semi-permanent Installation OWC

Design Concept 2 is a larger, semi-permanent OWC. In order to work across all tidal conditions without moving, the box would have to be much taller. As mobility is no longer considered, the footprint of the system can be increased, resulting in greater power production. Due to the greater volume of displaced air this system would require a greater radii chimney and turbine. As the structure would remain in one place and be largely submerged during high tide, the system would need to be strong enough so that currents and storms do not cause damage. The necessity of such high structural integrity drives up construction requirements and cost. The major disadvantage of this system is that in order to justify its high construction costs, the community would need to have sufficient confidence in its durability.

### 3.1.3 Design Concept 3: OWC on Tracks

Design Concept 3 is constructed in a similar way to the mobile OWC, with the addition of tracks along which the OWC would move, reacting to changing tidal conditions (Figure 3.2). To achieve this, external buoys would be fixed at the desired mean water height. As tides decrease, the weight of the OWC would cause the system to move down the beach until the buoys encounter water, at which point the buoyancy force would cause the system to stop. Similarly, as tides rise, the buoys would cause the system to move up the beach. The system would be sufficiently heavy such that individual waves would not cause significant displacement, but the system would still react to tidal movement. The track system would be difficult to construct, vulnerable to corrosion and would likely require constant realignment as a result of the shifting surface of the beach.
3.2 Bicycle Point Absorber System

The bicycle point absorber system is split into three subsystems (Figure 3.3). These are the ocean-land power transfer subsystem, the linear to rotational motion drivetrain subsystem and the flywheel to generator subsystem.

Figure 3.2: OWC on a track to accommodate for tides.

Figure 3.3: Land-based generator point absorber system.
3.2.1 Subsystem 1: Ocean-land Power Transfer

This system uses the vertical oscillating motion of a buoy to absorb wave energy and transfer it to a suspended mass in a land based drivetrain system. The energy is transferred between the buoy and suspended mass by a rope and pulley system as shown in Figure 3.4.

![Figure 3.4: Ocean-land power transfer system.](image)

The force produced by the buoy is equal to the weight of the water it displaces. For example, a 2L buoy in seawater of density $1025\text{kg/m}^3$ could produce 20.1N of force (enough to lift slightly more than 2kg). Extra buoys should be added or removed from the assembly in order to comfortably lift the hanging mass.

The first pulley drawn in the diagram rests on the sea floor. Used in these conditions, it would have performance issues due to the harsh environment (corrosion, sand, organic matter, currents). The cable from the buoy to the hanging mass passes through the pulley and hence changes direction.

As shown in Appendix A.2.2, there is a direct relationship between the mass of the suspended weight and the gravitational potential energy produced by the system. In order to increase the output of the system, the mass of the suspended weight could be increased, and a larger buoy would be used.

3.2.2 Subsystem 2: Linear to Rotational Motion Drivetrain

The linear motion of the cable would be converted to rotational motion through the use of a bicycle drivetrain. In drivetrain concept 2.A (Figure 3.5), the front wheel of a bicycle is used as the second pulley, and the mass is rigidly connected to the bicycle crank. As the mass rises and stores gravitational potential energy, the crank back pedals with a low energy loss. As the mass falls, the crank is pulled, transferring the potential energy to rotational energy in the drivetrain.
Similarly, for drivetrain concept 2.B, a length of bicycle chain is incorporated as a component of the transfer cable connected to a hanging mass. This drives the front chain wheel directly. The regular bicycle chain remains to transfer power from the front chain-wheel set to the back wheel. A bicycle with more than one front gear is necessary. Similar to drivetrain concept A, the mass is free to move up, and drives the back wheel as it falls.

In both concept 2.A and concept 2.B, it is envisaged that with sufficient buoy movement and gearing, the rear bicycle wheel would be regularly propelled and constantly spinning, behaving similarly to a flywheel. This consistent rotational motion would allow the bicycle point absorber system to continually produce power.

Design concept 2.A has limited scope for adjustment in order to perform at different wave heights due to the rigid connection between the hanging mass and the bicycle crank. In this case, the motion of the mass is limited to the vertical range of the pedal. In design concept 2.B, the length of chain incorporated in the transfer cable can be lengthened to accommodate tidal variance. At high tide, the hanging mass would oscillate near the chain wheel. At low tide, the hanging mass would oscillate near the ground. For example, in an unaltered system a tidal movement of 2m would result in the mass oscillating as low as 2m below the chain wheel.

In order for the system to operate across a range of tidal levels, a mechanism could be made to shorten the length of the transfer cable at low tide. This could be as simple as tying a loop in the transfer cable in a section between the two pulleys. This solution would work for both concept 2.A and concept 2.B. Therefore, this system requires manual adjustment.

For design concept 2.B, the bicycle could be hoisted such that the mass oscillates freely over an extended tidal range. Compared with shortening the length of the transfer cable this solution would require more initial effort to construct, but could be left unattended for greater periods of time.
3.2.3 Subsystem 3: Rotational Motion to Generator

In concept 3.A (Figure 3.6), a generator is connected directly to the rear wheel shaft. This would require modifications to the wheel hub as with most bicycle wheels the hub is free to spin around the fixed rear axle. In this case, the user is free to adjust the gear of the bicycle in order to optimise power output to wave conditions. A generator that would operate in the correct torque and RPM range would need to be acquired.

![Figure 3.6: Flywheel to generator drivetrain subsystem concept 3.A: Generator on rear-wheel shaft.](image)

In concept 3.B (Figure 3.7), a chain is run from the rear chain wheel sprocket to an independently mounted chain ring, which could be connected to a generator. This does not allow the user access to the full rear chain sprocket to adjust gearing during operation.

![Figure 3.7: Flywheel to generator drivetrain subsystem concept 3.B: Generator independently mounted, connected with a chain.](image)
Concept 3.C (Figure 3.8) works on similar principles to concept 3.B however instead of using a chain to transmit power, a belt is used. This subsystem allows the user to adjust the bicycle gearing along the full breadth of the rear chain cassette in order to optimise generator performance to wave conditions. It should be noted that belts generally transmit power at a lower efficiency than chains.

![Figure 3.8: Flywheel to generator drivetrain subsystem concept 3.C: Generator independently mounted, connected via belt.](image)

### 3.3 Linear Generator Buoy

The linear generator buoy design concept will use the momentum of a magnet freely bouncing within a solenoid to induce an electric current, as shown in Figure 3.9. The electrical generation system is self-contained inside the buoy and will be connected to an external battery charging station. The anchor is included to keep the buoy upright. Depending on experimental results of voltage and current output of the system, several linear generator buoys could be arranged in series or parallel in order to efficiently charge a battery.
Figure 3.9: Linear generator buoy design concept.

This design could potentially be made entirely from repurposed materials. For example, the housing could be made from PET bottles sealed with glue. Magnets could be repurposed from old speakers, and elastic bands could be used to suspend the magnet. Copper wire for the solenoid could be salvaged from many types of old electrical machines. For example, cathode-ray tube television screens contain much more wire than would be required in one of these devices.

Alternatively, for an optimised system, PVC pipes could be used for the housing. This would provide a more consistent solenoid width. A rare earth magnet could be used in place of the speaker magnet for a larger magnetic flux in the solenoid and therefore more power is produced. Under repetitive loading, the elastic band suspending the magnet may snap. Instead, a length of bungee cord or a spring could be considered. Several of these buoys could be connected to the same external battery charger, which could potentially be mounted on a jetty, boat or on-shore. This is the only design concept where all mechanics are entirely within a sea-based system, and as such it does not require any adjusting mechanism to respond to changing tidal conditions.

3.4 On-shore Tapered Wave Channel Device

Figure 3.10 shows the tapered wave channel design concept. This is a shore based adaptation of the overtopping concept discussed in the Subsection 1.2.3. As waves break on the beach, they are captured in the reservoir. Then as the wave recedes back to sea, the water trapped in the reservoir gains gravitational potential energy. The reservoir has a small outlet with a turbine, and the gravitational potential energy of the captured water is converted into rotational energy in the turbine shaft, which works a generator.
3.5 Summary

A series of potential design solutions has been generated on the principles of existing oscillating water column, point absorber and tapered wave channel systems. The design solutions face issues with respect to the operating environment including tidal variations, corrosion, high force loadings and small-scale feasibility. Furthermore, the potential materials have been considered with respect to their availability and suitability.

The construction would need to consider structural requirements and be anchored to the beach to avoid being moved by waves. Additionally, the reservoir needs to be watertight to retain the water while waves are receding to sea. These objectives could be achieved by using plastic sheeting and a series of pylons. The plastic sheeting would extend beneath the surface of the sand in order to reduce water seepage.

For this concept to be successfully prototyped, the generator and all electronics would have to be securely waterproofed. A failure of the waterproofing system would cause the electronics to short circuit, resulting in catastrophic failure. This design concept has no adjusting mechanism for continual operation in changing tidal conditions. Owing to the reservoirs structural requirements, the system would not be readily transportable. Serious implementation of this concept in the third world would require an ocean environment with low tidal movement, or the development of an efficient tide height adjustment mechanism.

Figure 3.10: On-shore tapered wave channel design.
Chapter 4

Concept Evaluation

The design concepts were evaluated against their potential output, practicality and ease of construction. It was decided that the bicycle point absorber system and two versions of the linear generator system would be selected for prototyping. The bicycle point absorber system was selected for its potential high power output and practicality as a linear-to-rotational energy converter. Linear generator buoys were selected for their simplicity and ability to be up-scaled.

4.1 Potential Power Output

Appendices A.2.1 to A.2.4 show calculations for potential power outputs of the oscillating water column, bicycle point absorber, linear generator buoy and on-shore tapered wave channel respectively. Table 4.1 shows calculated charging times for a car battery, smartphone and to operate an LED Africa lantern for 3 hours (detailed in Section 2.7).

Table 4.1: Charging time for different example applications.

<table>
<thead>
<tr>
<th>Application</th>
<th>Oscillating Water Column</th>
<th>Bicycle Point Absorber</th>
<th>Tapered Wave Channel</th>
<th>Linear Generator Buoy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Battery</td>
<td>1100</td>
<td>127</td>
<td>22.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Smartphone</td>
<td>7</td>
<td>0.8*</td>
<td>0.14*</td>
<td>87**</td>
</tr>
<tr>
<td>LED Africa</td>
<td>20</td>
<td>2.3</td>
<td>0.4*</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* It should be noted that these charging times are a reflection of the maximum capacity of each system for assumed wave conditions. In application, charging voltage and current will be regulated to avoid damaging the battery.

** For an array of 10 linear generator systems, smartphone charging time is reduced to 8.7 hours.

Table 4.1 shows that the bicycle point absorber and tapered wave channel are both theoretically able to charge a variety of battery types within a short time frame. In comparison, the OWC and linear generator buoy have slower charging times. The OWC could still charge a smartphone in 7 hours, which is a reasonable time and provides the option of charging a phone overnight while sleeping and using the phone during the day. Additionally, the OWC could provide enough charge to run an LED Africa lantern for three hours by charging for 20 hours. The linear generator charging times are not theoretically feasible unless up-scaling is considered. A system of 10 linear generators connected to one central charging station could charge a smartphone in approximately 9 hours, which is a
reasonable charging time. The lower power output of the OWC and linear generator is a drawback of the systems compared to the bicycle point absorber and tapered wave channel systems, though they remain feasible design concepts.

4.2 Suitability for Application

The ability of each design concept to be built from repurposed materials and perform as designed in its operating environment is a fundamental factor when assessing a design concept’s feasibility for inclusion in the guidelines. Table 4.2 shows a comparison of the concepts’ suitability for application.

Table 4.2: Design suitability for application ratings.

<table>
<thead>
<tr>
<th>Design Concept</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillating Water Column</td>
<td>Medium</td>
</tr>
<tr>
<td>Bicycle Point Absorber</td>
<td>High</td>
</tr>
<tr>
<td>Tapered Wave Channel</td>
<td>Low</td>
</tr>
<tr>
<td>Linear Generator Buoy</td>
<td>High</td>
</tr>
</tbody>
</table>

The OWC was given a medium rating for its vulnerability to corrosion and lack of a feasible adjusting mechanism according to varying tides. As the OWC is the only design concept that uses air as a working fluid, it induces less torque on the turbine. For this reason, the effectiveness of the OWC is particularly prone to friction in turbine bearings. The moist environment that the OWC would operate in may cause turbine bearings to corrode, resulting in decreased efficiency and life span. Additionally, the proposed automatically-adjusting track system was deemed unrealistic due to the changing nature of beach surfaces. Aside from these corrosion and tide issues, the OWC was deemed suitable for application and given a medium suitability for application rating.

Most moving parts of the bicycle point absorber are land-based; therefore, it is less prone to corrosion than the OWC and tapered wave channel design concepts. Parts that are immersed in water can be made from non-corrodible or corrosion-resistant materials. No automatically adjusting mechanism for changing tide heights has been developed but can be done manually by adjusting the length of the power transfer cable. For its low vulnerability to corrosion and tidal-adjustment mechanism the bicycle point absorber was given a high suitability for application rating.

The tapered wave channel design requires a turbine that is frequently immersed in water, and either a waterproof generator, or energy transfer system to an out of water generator could be used. Considering that the systems are intended for construction from repurposed materials, the prospect of a safely operating waterproof generator was considered improbable. Any drivetrain system used to transfer the energy to an above water generator would be prone to corrosion. For these reasons, the tapered wave channel was given a low suitability for application rating.

The linear generator buoy concept could be made entirely watertight from non-corrodible materials (PVC pipe, PET bottle). As the system is sea-based, and can be connected back
to an above-water charging station by cable, it is unaffected by tides. In addition, the system was considered suitable for up-scaling. If required, an array of linear point absorbers could be connected and power the same charging station. For these reasons, the linear generator buoy design concept was given a high suitability for application rating.

4.3 Assessment

Due to the high suitability for application rating and potential power output, the bicycle point absorber design concept was selected for prototyping. More specifically, a prototype comprising of Subsystem design concepts 1, 2.B and 3.B was selected. Subsystem 2.B was selected over Subsystem 2.A because the use of a chain section on the power transfer cable restricts the hanging mass to vertical motion, increasing the efficiency of the system. Subsystem 3.B was selected because it allows for higher gear ratio than Subsystem 3.A, and avoids the use of a belt as required in Subsystem 3.C.

The linear generator design concept was selected due to its high suitability for application and, importantly, the ability to be up-scaled. Even though the linear generator concept may not produce as much power as the other systems, potential up-scaling means an array of replicated smaller systems may still achieve a community’s power requirements. Two versions of the linear generator design concept were selected to be prototyped. One prototype with materials that can be found in scrap yards easily, such as PET bottles and speaker magnets, and an optimised prototype using some purchased components.

4.4 Summary

On the premise of their suitability for application and potential power outputs, the bicycle point absorber and linear generator buoy designs were selected for prototyping. These concepts were judged best suited for development and inclusion in the guidelines. The tapered wave channel and OWC designs were not selected due to their vulnerability to corrosion and lack of tidal adjustment mechanisms. The tapered wave channel and OWC design concepts were not investigated further.
Chapter 5

Bicycle Point Absorber Prototype

The bicycle point absorber was considered a priority for prototyping and testing as it was deemed to be the most effective solution as detailed in Section 4.3. Motors from a printer and ceiling fan were adapted for use as generators in the system. A wooden frame was constructed with hand tools to mount the generators to the bicycle wheel and initial testing was promising, with the mechanics of the prototype fully functional. The completed system is worked by a buoy and counter weight attached to the drivetrain of the bicycle. This concept was continued as the final prototype with a full charge controller system.

Subsystem 1 was adjusted by having the buoy float directly on the surface of the water without a pulley anchored to the seafloor, achieved by filling the bottles 2/3 full of water. The hanging mass was redirected off of the jetty using a pulley as with the buoy. In Subsystem 2.B, two spools were attached with ropes coiled in reverse directions going to the buoy and hanging mass, working the bicycle drivetrain. Subsystem 3 was also changed to a new design where the generator was pressed against the bicycle tyre using a hinged frame with a tensioning spring.

5.1 Initial Construction

To best represent the abilities and resources of a remote community, the prototyping was based upon what scrap and recycled materials were readily available. A bill of materials is shown in Table 5.1 and shows both repurposed and purchased materials. More detail on the construction is given in the guidelines in Appendix C.

DC motors were the most direct solution for charging a battery and initial tests involved attaching them against the wheel rim. This was done by using hose clamps and angling the motor spindle up against the rim. The motors needed to contact the rim so that there was enough friction for them to work, but not enough such that the bicycle motion was hindered. Open circuit voltages (0-15V) and short circuit currents (0-0.3A) were peaks when manually working the bicycle and not representative of the actual operation of the system. Most importantly, DC motors are not designed to run as generators, especially for an extended period of time outside of their operating range. As the completed WEC should operate for extended periods of time and with large, powerful waves, the brushes of typical small DC motors would wear quickly wear and render the machine useless. Therefore, the use of DC motors from a printer was not considered the best solution.
Another viable solution was to retrofit an existing AC induction machine. To do this, a common ceiling fan was disassembled and small cylinder magnets were arranged with steel banding on the housing of the ceiling fan, turning it into a permanent magnet AC generator suitable for use in our system (Appendix C). This generator has the benefits of being easy to source, manufacture, includes reliable bearings and will not wear out. Most domestic ceiling fans have two sets of windings corresponding to different speed or winter and summer settings. These can be used simultaneously in series to increase the voltage or in parallel to increase the current. It is important to take into account that if they are used together, there will be a phase difference between the power outputs. However, as DC power is needed to charge a battery, this problem is solved by rectifying the AC power to DC power and then connecting the two circuits.

To support and house the generator, a simple wooden frame was constructed which also served the purpose of securing the bicycle. As can be seen in Figure 5.1, the generators rested lightly upon the bicycle wheel with a tensioner spring. As two identical ceiling fans were available, two generators were made.

A few different concepts were considered and tested for the drive system of the bicycle. The use of a secondary chain to drive the crank set was tested and was a viable option, however issues with the chain falling off meant that a guidance system would be necessary. The final prototype used two hand fishing reels as spools, rigidly fixed to the drivetrain. Ropes were wrapped on each of the spools in opposing directions, with a ‘driving’ rope attached to the buoy and the ‘returning’ rope to the counterweight. This allowed for any size wave to work the system and was also self-adjusting for tidal movements.

Table 5.1: Bill of materials for Bicycle Point Absorber Prototype.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Material</th>
<th>Repurposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bicycle</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>Spools</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>3L milk bottles</td>
<td>✓</td>
</tr>
<tr>
<td>-</td>
<td>Water for filling bottles</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30m rope or cable</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Rare earth magnets</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>Small DC motors</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>Ceiling Fans</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>Assorted nuts and bolts</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Wooden screws</td>
<td></td>
</tr>
<tr>
<td>4m</td>
<td>Wood planks and board</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Drill and bit set</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Zipties or other fasteners</td>
<td></td>
</tr>
<tr>
<td>5kg</td>
<td>Metal banding</td>
<td></td>
</tr>
</tbody>
</table>

Another viable solution was to retrofit an existing AC induction machine. To do this, a common ceiling fan was disassembled and small cylinder magnets were arranged with steel banding on the housing of the ceiling fan, turning it into a permanent magnet AC generator suitable for use in our system (Appendix C). This generator has the benefits of being easy to source, manufacture, includes reliable bearings and will not wear out. Most domestic ceiling fans have two sets of windings corresponding to different speed or winter and summer settings. These can be used simultaneously in series to increase the voltage or in parallel to increase the current. It is important to take into account that if they are used together, there will be a phase difference between the power outputs. However, as DC power is needed to charge a battery, this problem is solved by rectifying the AC power to DC power and then connecting the two circuits.

To support and house the generator, a simple wooden frame was constructed which also served the purpose of securing the bicycle. As can be seen in Figure 5.1, the generators rested lightly upon the bicycle wheel with a tensioner spring. As two identical ceiling fans were available, two generators were made.

A few different concepts were considered and tested for the drive system of the bicycle. The use of a secondary chain to drive the crank set was tested and was a viable option, however issues with the chain falling off meant that a guidance system would be necessary. The final prototype used two hand fishing reels as spools, rigidly fixed to the drivetrain. Ropes were wrapped on each of the spools in opposing directions, with a ‘driving’ rope attached to the buoy and the ‘returning’ rope to the counterweight. This allowed for any size wave to work the system and was also self-adjusting for tidal movements.
5.2 Initial Testing

The ceiling fans had two coils with a nominal usage rating of 240\,V and 0.7\,A. Theoretically these are the maximum value outputs of each coil. Working the system by hand gave open circuit voltages of up to 200\,V. This showed that step down transformers would be necessary and that they would need to be placed in parallel to provide a battery charging range of voltages. Issues of magnet movement due to the banding coming loose were identified and the banding was stabilised with glue.

5.3 Interpretation and Potential Improvements

This prototype was continued as the final design and the electrical components were constructed to convert the AC high voltage output to a charging DC voltage. The generator could be improved upon if the magnets were brought in closer to the generator coils to reduce the air gap. This is done as the magnetic field strength dissipates with distance at an inverse squared proportion. Multiplying the number of magnets per coil will also increase field strength, as long as the magnets do not overlap neighbouring coils. Finally if the mechanical system can manage the extra resistance of more generators, then additional fans could be added to the system.

5.4 Summary

Two generator options were explored for the bicycle point absorber and the modified ceiling fan was the best solution. The system was made more efficient by changing the buoy and drivetrain and continued as the final prototype due to successful initial tests. Further
improvements were proposed for the generator and it was identified that transformers were necessary as the voltage ranges were too high to charge a 12V battery.
Chapter 6

Linear Generator Buoy Prototypes

Two variants of the linear generator buoy concept were selected for prototyping, one made entirely from repurposed materials, and another from a combination of repurposed materials and low cost materials. Upon preliminary testing, it was found that both prototypes required unreasonably vigorous operation to achieve a desired power output. Options for increasing performance were considered but not pursued as it was judged to have less potential than the bicycle point absorber prototype.

6.1 Initial Construction of Prototype from Repurposed Materials

The bill of materials for the linear generator buoy from repurposed Materials is included in Table 6.1, and the completed prototype is shown in Figure 6.1. A ceramic magnet from a stereo was salvaged, and found that the diameter was suitable for a 1.25L PET bottle. The ceramic magnet was suspended on a length of elastic attached to the lid of the bottle. Salvaged copper wire was wrapped around the mid-section of the 1.25L PET bottle, completing the linear generator. The end of the electrical cord was stripped and tied into the copper wire, allowing the generated electricity to be connected to a central charging unit. Two 2L PET bottles were cut in half and connected bottom to bottom to create the outer case of the system, into which the linear generator was mounted. A hole was drilled into the lid of one of the 2L bottles, through which the electrical cord exited the system. All gaps were sealed with silicone caulk.

Table 6.1: Bill of materials for Linear Generator from scrap.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Material</th>
<th>Repurposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2L PET bottles</td>
<td>✓</td>
</tr>
<tr>
<td>1</td>
<td>1.25L PET bottle</td>
<td>✓</td>
</tr>
<tr>
<td>1</td>
<td>100m of 1mm diameter insulated copper wire</td>
<td>✓</td>
</tr>
<tr>
<td>1</td>
<td>Ceramic speaker magnet</td>
<td>✓</td>
</tr>
<tr>
<td>1</td>
<td>5m electrical cord</td>
<td>✓</td>
</tr>
<tr>
<td>1</td>
<td>20cm length of elastic</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>silicone caulk</td>
<td></td>
</tr>
</tbody>
</table>
6.2 Initial Construction of Prototype from Purchased Materials

The bill of materials for the linear generator buoy from purchased materials is included in Table 6.2, and the completed prototype is shown in Figure 6.2. Two neodymium magnets were connected on both ends of a socket with opposing polarities to maximise change in magnetic flux. These magnets were then glued to the midpoint of the length of elastic. The end of the elastic was glued to the end of the 25mm diameter PVC pipe, so that the magnet assembly was free to bounce inside the pipe. Copper wire was wrapped around the midsection of the PVC pipe, in the oscillating range of the magnets, completing the linear generator assembly. This assembly was placed inside the 50mm diameter PVC pipe and capped on both ends. The coil ends were attached to electrical cords and threaded through drilled holes in an end cap. Gaps around the electrical cord and PVC end caps were sealed with silicon caulk.

Table 6.2: Bill of materials for Linear Generator from purchased materials.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Material</th>
<th>Repurposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30cm of 25mm diameter PVC pipe</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30cm of 50mm diameter PVC pipe</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>50mm diameter PVC pipe end caps</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100m of 1mm diameter insulated copper wire</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>(22mm diameter × 10mm height) Neodymium magnets</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15(mm) size socket</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20cm length of elastic</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>silicone caulk</td>
<td></td>
</tr>
</tbody>
</table>
6.3 Initial Testing

Both prototypes were tested manually and the electrical output measured with multimeters. As such, no steady state was achieved and readings were only estimate figures for true performance. Initial testing of the prototype from repurposed materials showed that for realistic wave motion, negligible open circuit voltage was produced. Working the system vigorously produced an open circuit voltage of 0.2\(V\). It was considered that the ceramic speaker magnet was too weak to induce a sufficiently strong electromagnetic force in the solenoid to create meaningful power. When replacing the ceramic magnets with neodymium magnets in the purchased materials prototype, and then working the system vigorously, an open circuit voltage of 1.4\(V\) was achieved.

6.4 Interpretation and Potential Improvements

Based upon the initial testing results, the prototype from repurposed materials was not considered to have sufficient potential to meet the stated goal of providing a rural community with minimum power requirements, and so was not developed any further. The prototype from purchased materials was considered more suitable for development. Further opportunities for improvement include a steel layer outside the copper windings, which would increase the magnetic flux and therefore extractable power. To increase performance, more copper windings and magnets would be necessary.

Concerns were raised regarding the design of a central charging station that could efficiently receive outputs from an array of point absorber buoys. Additionally, the orientation of the buoys in water needs to be addressed. They must either be buoyant and connected to an anchor, or under the surface the water and connected to a float. Considering the
performance of both prototypes in initial testing, and potential problems in integrating systems to charge a central battery, the linear generator buoy systems were not pursued further.

6.5 Summary

Two prototypes of the linear generator buoy system were constructed. One was made from repurposed materials, and the other from materials readily available for purchase. After considering the results of manually working both systems, and considering integration issues of an array of systems, it was decided that neither prototype should be pursued further. All efforts were directed to the bicycle point absorber which had the best potential to meet the goals.
Chapter 7

Experimental Method

The WEC prototypes were tested for performance with controlled wave conditions in the School of Civil, Environmental and Mining Engineering (CEME) wave flume, and then tested in field at Brighton Beach, South Australia. Testing in the wave flume allowed for initial assessment of the power produced by the WEC prototypes in consistent conditions. In-field testing then verified that the prototypes could replicate their laboratory behaviour in real world application. The testing results provide evidence for the recommendations made in the guidelines in Appendix C.

7.1 Laboratory Testing

Laboratory testing altered greatly from prior expectations due to insufficient wave amplitude conditions. The wave flume offered by CEME, is approximately 32m long, 1.5m wide with a maximum depth of 1.2m. The advantage of the wave flume is that wave conditions can be controlled accurately, facilitating data collection, however the largest amplitude achievable is 6cm over a frequency range of 0.8-1.5Hz. A WattsVIEW power monitor was used to record the measurements of the voltage and amplitude produced by each prototype. From this, the total power produced by each prototype for all wave conditions could be calculated.

The laboratory experimental procedure is:

1. Secure a ruler to the sidewall of the wave flume test section.
2. Fill the wave flume with water to the desired height.
3. Place the buoys into the flume and attach it to the WEC.
4. Connect WEC to the voltage data logger.
5. Set the wave paddle to largest state. Steady state can be verified by observing maximum and minimum water heights on the ruler.
6. Measure voltage and current output on the data logger for 30 seconds.
7. Turn off the wave flume paddle and wait until the WEC prototype is stationary.
8. Remove the WEC prototype.

Since there are limitations in the wave properties produced by the wave flume, dimensional analysis was considered to extrapolate results for a larger range of wave properties. Due to the complexity of accurately modelling electrical power output of generators by dimensional analysis, it was not a part of the data analysis plan and was considered outside of the scope of the project.
7.2 In-field Testing

In order to verify the laboratory testing results, the prototypes were tested in-field at Brighton Beach. Due to the inherent variability of ocean waves the WEC was be tested over 3 minute periods to find an overall power output value.

The in-field experimental procedure is:

1. Find wave conditions via surf reports online. This will include frequency and wave height.
2. Place the buoys over the side of the jetty, into the water.
3. Connect buoys to the WEC, making sure to thread the rope through the pulley.
4. Connect the data logger.
5. Measure voltage and current output on the data logger for 3 minutes.
6. Remove the WEC prototype.

7.3 Summary

Laboratory testing was used to identify power being produced for the small flume conditions of 6cm amplitude waves. In-field testing was used to verify that the WEC prototypes can successfully produce a charging voltage and current. Testing occurred on days when surf reports identified 70cm waves. All data collected will be presented in graphs that identify current, volts and power against time.
Chapter 8

Results

The bicycle point absorber prototype was tested in the wave flume and in-field several times throughout the year to continually obtain power output results as the system concept was altered. In the wave flume, open circuit voltages for the system were obtained at 200Ω, 350Ω to verify that power was being produced. Due to the small wave conditions, the WEC output data was too small to be able to charge a battery but did prove that power was being produced. Further testing was necessary in-field to check that the system could function correctly for larger waves. As the system design was iteratively improved upon, simple testing on the flywheel and capacitors used were necessary to show that they aid in the charging process. As the voltages produced were much greater than required to charge a battery, two transformers were used to step down the voltage to a range suitable for the purchased charge controller. The final field test identified the minimum wave height necessary to consistently charge a 12V battery with the entire electrical system and charge controller in use.

8.1 Wave Flume Results

The power output of the bicycle point absorber prototype in the wave flume is included in Figures 8.1 and 8.2. Since the waves produced in the flume were small, only one of the two generators was connected. This reduced the load on the drivetrain and the spikes in the generated power. Since the wave flume was not capable of producing waves within the intended operating range of the prototype, data was only taken for the maximum wave height. Other conditions were briefly tested, and the effect was unremarkable.

For the maximum 6cm amplitude condition, tests were conducted for open circuit voltage and resistive loads (200Ω, 350Ω). This allowed us to compare the maximum voltage with resistive voltages and also investigate the power produced under these loads. From Figure 8.1, it can be seen that under a load, the system is not optimal for small wave conditions. Figure 8.2 shows that the system is capable of producing power in the range of 0.5-2W for the same conditions. Notably, the power output is greater for 350Ω load than 200Ω load. A car battery has an internal resistance in the order of 50-100mΩ, and so the behaviour of the system in charging the battery would be considerably different to those observed in the wave flume. This shows that the system successfully converts wave motion to electrical energy but that the conditions are insufficient to charge a battery.
Chapter 8 Results

Figure 8.1: Wave Flume Test 6cm amplitude, 1Hz frequency - Output Voltage (One generator containing two circuits, connected in parallel. 16 magnets).

Figure 8.2: Wave Flume Test 6cm amplitude, 1Hz frequency - Output Power (One generator containing two circuits, connected in parallel. 16 magnets).
8.2 Field Testing Results

The bicycle point absorber was field tested in waves of 0.60-0.70m height. To investigate a wider operating range, the 350Ω load was changed for a 50Ω load. Figures 8.3 and 8.4 show the potential difference, current and power produced for nominal 200Ω and 50Ω loads. This allows us to investigate the extractable power under the given conditions. Figure 8.5 shows a comparison of the produced power of each condition. Wave conditions on this day were considered within the operating range of the prototype, and so both generators were connected to the drivetrain. This provides a total of four generating circuits (two per generator), and these were arranged in parallel to increase current.

Looking at the 200Ω and 50Ω resistive load characteristics, a reasonable level of voltage and current is observed. Up to 1.9A was produced which can be considered significant as the maximum theoretical amperage of the generators is 2.4A. This corresponds to the four coils which are each rated at 0.7A. It can also be seen that the power produced is delivered in spikes which was expected from infrequent wave motion. While the voltage ranges look suitable for charging a 12V battery (charges in the range of 12-14V), the results cannot be directly compared as a battery is not a pure resistive load. Furthermore, typical internal resistances of 12V lead acid batteries are in the order of 10mΩ [57]. A systematic error of 0.1A was identified in the WattsVIEW power monitor during testing and the cause was not identified. This does not have a significant effect on the results and was adjusted for. The voltage and current were verified with the use of multimeters.

Figure 8.3: Field Test - 200Ω characteristics.
Figure 8.4: Field Test - 50Ω characteristics.

Figure 8.5 reaffirms the observed behaviour in the wave flume that the prototype produces less power for a smaller load (50Ω) than a larger load (200Ω). These results show that under the right conditions, the prototype is capable of producing between 20-30W; however, due to the erratic nature of waves and the produced power curves, this power is not necessarily useful. As per the stated aims, the prototype must still be modified to charge a battery. As the nominal loads were selected to display the operating characteristics of the system, the results do not represent the maximum power output available. Rather, it has been shown that the design does generate significant power from waves of 0.60-0.70m in height. With further investigation into the electrical system and different generators, it has the potential to more than adequately charge a 12V lead-acid battery. To identify the maximum power output, the electrical impedance of the system must be investigated and as the solution is dependent upon a variety of factors and mainly material availability, was not deemed necessary.
8.3 Design Alterations

To charge a battery, a charge controller is needed as discussed in Section 2.6. There are numerous sources for charge controller designs publicly available and a good example of one that uses easily sourced materials was given in Section 2.6 [54]. This design has been proven to work from repurpose materials in 2014 by the aforementioned University of Adelaide honours team that created a set of guidelines on the construction of wind turbines from repurposed materials [14]. To best utilise the team’s resources and avoid reworking known concepts the charge controller specified in Section 2.6 was not built. Rather, a solar charge controller (Kemo M149) was bought off the shelf and incorporated into the system. The charge controller is rated to a maximum open circuit voltage of 30\(V\), which is considerably lower than the observed open circuit voltage of the prototype. In order to keep the output of the prototype within the operating range of the charge controller, 6:1 transformers were salvaged. By transforming the circuit output and switching between parallel and series arrangements, power conditions to match wave conditions can be achieved. The completed circuit diagram and built system is included in Figures 8.6 and 8.7.
To reduce the peaking nature of the produced power, two options were considered and implemented. Firstly, the rotational inertia of the drivetrain was increased by adding 5kg of steel banding to the inside of the bicycle tyre, as shown in Figure 8.8. The increase in rotational inertia will reduce the top speed of the drivetrain and deceleration of the drivetrain due to the electromagnetic forces in the generators. A simple drop test was conducted to evaluate the effect of the extra banding. Away from any field environment, the prototype was worked by attaching a 12kg weight to the power transfer cable, and allowing it to fall 135cm. This simulates the falling of the buoy after a peak in a wave. The results with and without the steel banding are shown in Figure 8.9.
8.3 Design Alterations

Figure 8.8: Flywheel constructed with steel banding in bicycle tyre.

Figure 8.9: Flywheel drop test and potential difference across battery terminals.
Figure 8.9 suggests that the steel banding worked as desired. At approximately 6.4 seconds, the lower inertia system produced a larger voltage, inferring a greater top speed than the higher inertia system. At 8.3 seconds, the low inertia system voltage dropped quickly, whereas the high inertia system continued charging the battery until 10 seconds. Both of these instances suggest that higher rotational inertia will reduce the peaky nature of the produced power.

In addition to changes to the mechanical system, a smoothing capacitor was implemented in the electrical system. A range of different capacitors were independently trialled in parallel with the charge controlled (as shown in Figure 8.6) in a drop test similar to that done with the flywheel; however, in this drop test the mechanical system was stopped immediately when the working mass hit the ground. In this manner, the charge stored in the capacitor that was available to charge the battery was isolated. The results are shown in Figure 8.10.

![Capacitor Drop Test](image)

Figure 8.10: Capacitor drop test potential difference across battery terminals.

Smaller value capacitors allowed the system to speed up faster, as implied by the larger voltage across the battery terminals in the first few seconds of the test. At the point where the weight driving the system hits the ground and the drivetrain is stopped (~9 seconds), the voltage across the battery terminals is no longer provided by the generator but by the stored energy in the capacitors. Following this point, a clear pattern arises as larger capacitors are able to discharge at higher voltage for a longer period of time than smaller capacitors. Based upon these results, the 10000\(\mu\)F capacitor was chosen. This is reflected in the completed electrical system in Figure 8.6.
8.4 Subsequent Field Testing

While the 10000µF was chosen for its better discharging capability, it is worth noting that this comes at the cost of a longer charge time for the capacitor itself. This is shown in Figure 8.11 where the charged capacitor plot was the one used for Figure 8.10 to compare characteristics when the system is running. It was noted that the smaller capacitors did not share the same charging characteristics and were much faster to charge.

![10000µF capacitor charge time characteristic.](image)

Figure 8.11: 10000µF capacitor charge time characteristic.

8.4 Subsequent Field Testing

By manually working the system it was observed that a larger torque was required to run the prototype due to the low electrical resistance of the battery, increased inertia of the drivetrain, increased cogging torque of the generator and inclusion of the capacitor. Considering the limitations of the waves that could be produced, testing in the wave flume was considered unnecessary. The system was field tested in 0.60-0.70m high waves, and the voltage and current across the battery terminals is shown is Figure 8.12.
The current flowing into the battery was negligible for most of the 10 minute test period, with the exception of some slightly larger waves. This shows that in the prototype’s current configuration and in wave conditions of 0.60-0.70m waves, meaningful power output cannot be achieved. It was also observed that extra light pressure applied to the system in addition to the working of waves was enough to produce measurable current. This infers that 0.70m is approximately the start-up wave height of the prototype, and below this level the produced voltage is not large enough to charge the battery. To confirm this, it would be necessary to field test on a day of greater wave height, but this was not possible due to calm ocean conditions.

8.5 Summary

Both wave flume and field testing showed that the bicycle point absorber prototype was capable of producing significant power, with peaks of 20-30W for nominal loads of 50-350Ω. Results also showed that the electrical output of the prototype was peaky in nature, and therefore not immediately useful. For example, it would not be able to continuously power a light, but rather the bulb would flash on and off with the frequency of the waves. In order to decrease the peaks, the rotational inertia of the drivetrain was increased, and a smoothing capacitor was installed to the electrical circuit. Transformers were also introduced to the circuit to step down the voltage and increase current, thereby making the electrical output more suitable for charging a battery. If an alternative generator more suited to the wave conditions was used to provide voltages of up to 30V, the upper limit of the charge controller, then transformers would not be necessary. With the addition of a cheap, commercially available solar charge controller, it was confirmed that the prototype was capable of charging a battery. Ocean conditions did not allow for further testing of
the effectiveness of the prototype to charge a battery in its appropriate range of wave conditions, nor confirm the adequacy of the smoothing alterations in enabling the prototype to power loads directly.

With these results, the WEC prototype has been confirmed to be able to produce power and charge a battery. As per the stated aims of the project, the document Guidelines for the Construction of a Wave Energy Converter from Repurposed Materials has been produced and is attached in Appendix C. They detail the process by which the current prototype was constructed and suggest recommendations and highlight pitfalls that may occur when building a WEC from repurposed materials.
Chapter 9

Discussion

The testing results (Chapter 8) have been compared to the performance of other power sources in order to assess the success of the bicycle point absorber system. A direct comparison with other WECs is not appropriate due to the vastly different power outputs of the systems, as well as the lack of pricing information for commercial WEC systems. A comparison was made with wind turbine systems made from scrap materials, and produced power was found to be similar for comparable conditions. The completion of the project goals was assessed in light of the testing results and the WEC construction guidelines produced (Appendix C).

9.1 Comparison of Results

In order to interpret the results meaningfully, it is necessary to compare the power produced and cost of the system with other technologies. For Figure 8.5, a 200Ω load results in an average power output of 4.3W and a 50Ω load results in an average power output of 3.5W. As shown in the Budget (Appendix B.5), essential parts to be purchased for the prototype cost a total of less than $100. Power output is heavily reliant on wave conditions, and the prototype has further modifications that have yet to be tested in-field.

9.1.1 Wave Energy Converters

The bicycle point absorber prototype operates at a much smaller scale than the other wave energy converters mentioned in the Literature Review (Section 1.2). The smallest wave energy converters in the literature, the “Wave Clapper” and the “Power Wing” by Eco Wave Energy, reportedly produce 5kW [41]. Since the cost of commercial systems is not publicly available, and the power output is in the order of 1000 times greater than the bicycle point absorber prototype, a fair comparison cannot be made.

9.1.2 Small-scale Power from Repurposed Materials

As discussed in the Introduction (Chapter 1), in 2014 an honours team at the University of Adelaide created a series of guidelines for the construction of wind turbines from repurposed materials. Since environments appropriate for wave energy converters are often quite windy, it is sensible to compare the power outputs of the two projects. The power produced by the wind turbines is included in Chapter 1.

In comparing the bicycle point absorber prototype to the horizontal axis wind turbine using a treadmill motor, for resistances of the same magnitude power outputs of between 3-5W were achieved. Considering the difference in load and the difficulty in comparing wind speeds with wave conditions, a more detailed comparison between the wind turbine using a treadmill motor and the bicycle point absorber prototype is not possible. The wind
turbine using a washing machine motor achieved significantly larger power outputs, how-
ever this prototype required fast wind speeds and a specific motor that may be difficult to
find in the developing world, and so a critical comparison with the bicycle point absorber
prototype is not possible nor fair.

Currently, another honours team at the University of Adelaide is developing guide-
lines on the construction of run-of-river hydropower systems from repurposed materials.
Although working towards similar goals as this project, the overlap between environments
suitable for implementing hydropower and wave power systems is considered minimal, and
therefore a comparison between power outputs of prototypes is not justified.

9.1.3 Community Power Requirements
As discussed in Section 2.7, a lantern as used by LED Africa consumes 5W and provides
sufficient lighting for six students to study comfortably. Powering direct loads and in
Adelaide wave conditions, the bicycle point absorber achieved an average power output
of 3-5W (Chapter 8). At times of favourable wave conditions, the bicycle point absorber
would be able to provide sufficient power to run an LED Africa lantern. For use in such a
direct application, a consistent power curve would be favourable. Modifications were made
to the prototype as discussed in Section 8.3, but further testing is required to confirm if
this has made the power curve appropriate for direct applications.

9.2 Assessment of Outcomes
There are three main objectives (Appendix B.1) that needed to be met in order to satisfy
the aims of the project. Firstly, the successful design of a WEC that can be constructed
from readily available materials and provide minimum power requirements for a com-
munity. Secondly, the successful construction and testing of a prototype design. Finally
a set of adaptable guidelines for WEC development were written based on experiences
from the prototype. Three further objectives that would improve the quality of the final
product were also identified Section 1.3. These objectives ensure that the system can be
left unattended for an extended period of time and be constructed by remote communities.

A series of concept designs were developed and are explained in Chapter 3. The de-
signs were evaluated in Chapter 4 for their ease of construction and potential to achieve
the required power. The prototype was constructed and tested successfully as detailed in
Chapters 5, 7 and 8. In light of this, the goals of both the design, successful construction
and testing of a prototype were achieved.

On a day with 0.70m waves the system was able to put charge into a car battery suc-
cessfully and safely (Section 8.4). Although only a small amount of charge was produced,
the final prototype only cost $271.36 and could be reduced to $100 if more repurposed
materials were used as shown in the budget (Appendix B.5). Considering this, the bicycle
point absorber is considered to have achieved significant power output for low construc-
tion cost. Based on current publicly available information, investigated WECs around the
world have not yet been proven commercially viable. The bicycle point absorber prototype
may have potential to become a small scale solution if future work is pursued (Chapter 10).
The final objective was to create a set of guidelines for the construction of a WEC system. A robust set of guidelines (Appendix C) have been created that explains the functionality of the system and suggests several alternative materials for each subsystem. A step by step construction process for the bicycle point absorber has been included with photos, which will enable users to successfully build their own system without in-depth construction or engineering knowledge. The guidelines also make users aware of common issues to avoid and are informative enough to show when changes in design are acceptable.

As the project construction, report, guidelines and testing were all completed in due time, the objective of proving the concept has been met. Data was collected both infield and at the wave flume, analysed and shown to have charged a 12V battery. The largest drawback was that the small waves around Adelaide did not provide a large enough input to charge a battery consistently. This problem could be solved with modifications as discussed in Future Work (Chapter 10).

To allow for the system to charge a battery over high and low tide changes, and therefore be left unattended addressing the first extension aim (Section 1.3), it needed to be self-adjusting for the ocean level. As the drive system used two counter-wrapped ropes over two spools, the system is able to automatically adjust depending on the buoy. Therefore, once the system is adequately secured to the jetty, it can continuously charge a battery unsupervised.

Regarding the second extension aim, the effects of corrosion were not examinable as the system was not left to work for an extended period of time. An effort was made to ensure that all corrodiible parts of the bicycle point absorber were positioned away from the water, on top of the jetty, which reduces susceptibility to corrosion. As the prototype is still exposed to the elements (salt water and air, humidity, rain), the system will inevitably corrode with time. While this problem is difficult to avoid, the use of mostly repurposed materials makes part replacement feasible. To reduce corrosion, the system could be covered, corrodiible parts could be replaced with plastic or other materials and the system should be routinely cleaned.

The bicycle point absorber prototype was constructed by the students outside of a workshop achieving the third and final extension objective. The system can easily be constructed with basic tools and by anyone following the guidelines. Considering this, the suggestions made in the guidelines can conceivably be implemented by a wide range of communities, including those without significant workshop expertise.

In the entirety of the project, each objective has been met and the bicycle point absorber prototype is a plausible, cheap, small scale solution for providing electricity to communities. Aspects of the system will need to be improved upon to justify its construction and use for charging a battery. These improvements have been suggested as future work, with the hopes that the University of Adelaide will continue to develop small scale systems from repurposed materials and find a solution that can produce more power.
9.3 Summary

The power output of the bicycle point absorber was compared to existing WEC systems, however due to the large differences in scale and cost, a critical analysis was not made. Since locations suitable for WECs are generally windy and also suitable for wind power, a comparison was made between the power outputs of the bicycle point absorber and small-scale wind systems built from scrap materials. It was found that power outputs were comparable for reasonable conditions. In light of the prototype testing outcomes and the produced guidelines, all objectives of the project were achieved.
Chapter 10

Future Work

The bicycle point absorber prototype accomplished the task of charging a battery and it was identified that 0.70m is the minimum wave height before the prototype can begin charging. There is significant room for future work in the area of improving the current prototype to charge a battery at a faster rate. Under certain load conditions significant power was produced, however this power was not suitable for immediate use due to the presence of large peaks and troughs. Modifications were made to keep the produced voltage consistently within the charging range, but this could be further improved by expanding the mechanical system into an array of buoys that connect to the same drivetrain, thereby producing more frequent pulses to drive the generator. In the event that a system with an array of buoys is found to generate usable power, the prospect of commercialising the concept should be considered. Furthermore, alternative generators that operate at a lower speed should be investigated which may remove the need for transformers.

10.1 Improvements

Charging a battery with the prototype was achieved but at an inconsistent and slow rate deemed unsatisfactory for general use 0.70m waves. In order to improve performance, other types of generators should be tested in the same system along with matching electrical components such as transformers and capacitors. Considerations should also be given to the type of power needed as varying generators could produce DC or AC electricity. Induction generators were not investigated due to their need for reactive power but could be considered. For example, the electrical system of a car and the alternator may be used as it is designed to charge a 12V battery. It is plausible that in the developing world, in the event of a mechanical failure or collision, a car’s entire electrical system may be salvageable. It is important to note that a high speed and torque will be required for a car alternator to remain magnetised and operate as a generator. Alternatively, there are motors and generators designed to operate at lower speeds and voltages which would better suit the prototype.

10.2 Direct Power

The constructed prototype was observed to provide a significantly larger power output for greater loads than the internal resistance of a 12V battery. The problem with using the prototype in it’s current state is the large peaks and troughs of the electricity produced. By creating a prototype with several buoys spread perpendicular to the wave front (Figure 10.1), the drivetrain would receive more frequent pulses and create a smoother electrical waveform. This array would act in a similar way to pistons in an engine working a camshaft. With these modifications, the prototype would be suited to provide direct power such as for running a lighting system.
Chapter 10 Future Work

Figure 10.1: Example layout of an array of buoys to deliver impulses to the drivetrain at a higher frequency

10.3 Commercialisation

The prototype produced was made from predominantly repurposed materials, and it is likely that with a generator chosen specifically for the purpose and conditions, the power output of the system would be significantly increased. If this was coupled with the array system as proposed in Section 10.2, then it is possible that the power curve would be made sufficiently consistent to enable immediate use of the produced power. This power could be used to supply the lighting system of the jetty upon which it is mounted, removing the need for grid power. Alternatively, the system could be connected to a micro-controller and thereby synced to grid frequency, allowing for the sale of power into the electricity grid. Small scale domestic power generation in the form of solar and wind are big industries and there may be a similar market for wave power.

10.4 Summary

There exists significant scope to build on the work completed in this project. The prototype system does not charge the battery as well as desired, and so other components should be trialled. A generator designed for lower voltage and higher current such as a car alternator or washing machine motor would be more suitable. By expanding the prototype to be worked by an array of buoys, pulses will work the generator at a higher frequency, resulting in more consistent electrical output. This may result in the system being suitable for direct applications such as lighting. Should the system be successfully modified to produce consistent, usable power, and store the power effectively, the prospect of commercialising the project should be considered.
Chapter 11

Conclusions

Research has shown that rural electrification is a key contributor to global development. Existing renewable energy technologies are being implemented in some regions by NGOs in order to drive progress. By producing guidelines for the selection and construction of renewable energy technologies from low-cost or repurposed materials, the aim of this project is to facilitate independent rural electrification.

NGOs working in the rural electrification space are generally using solar and wind installations to achieve their aims. A previous University of Adelaide mechanical engineering honours project has created guidelines for the construction of small-scale wind turbines from scrap materials. Similarly, another University of Adelaide team is currently producing guidelines for run-of-river hydropower systems from scrap. Considering the high technology requirements of solar photovoltaic cells, the development of a solar energy system was not considered a viable option. A gap in knowledge was identified regarding the development, construction and implementation of small-scale wave energy systems from low cost and repurposed materials.

Research was done into all WEC types to reverse-engineer them into potential concept solutions that could be made from repurposed materials. A dominant WEC design has yet to emerge, but several concepts are in their demonstration phase. Challenges to designs found in the literature included the irregularity in wave conditions, structural loading in the event of extreme weather conditions and the conversion of low frequency waves to usable, consistent power. Other design issues identified included tidal changes and corrosion. Considering this and the resources available to a remote community, the main and further objectives of the project were developed. No existing designs were feasible for direct down-scaling and so to achieve the aim of the project, a clean slate design approach was taken leading to a new concept solution.

Two linear point absorbers prototypes were developed, of which two variations were constructed; one entirely from repurposed materials and one from low cost materials. After manually working each linear generator buoy and considering the observed behaviour and power output, it was decided that the concept had limited potential and did not warrant further development and testing.

A bicycle point absorber concept was also designed, which is a land-based system. This design uses cables and an adapted bicycle drivetrain to transfer energy from the wave to rotational kinetic energy and run a generator. The prototype was built from predominantly repurposed materials, and developed over a series of testing and building iterations. Variations of the final design were tested in laboratory conditions in the School of Civil, Environmental and Mining Engineering’s wave flume. Testing was also done in-
field at Brighton Beach in South Australia, and achieved an average power output of 3-5W for loads of 200-350Ω in wave heights of 0.60-0.70m. It was observed that the behaviour of the system in-field was consistent with laboratory testing. Through the use of a commercially available solar charge controller, the prototype successfully stored power in a 12V battery.

Based on the experience of constructing and testing the bicycle point absorber prototype, guidelines of recommendations for building wave energy converters from repurposed materials were developed. These guidelines explain different options for constructing each subsystem of a bicycle point absorber, and the required considerations for integration between subsystems. An effort was made to highlight lessons learnt in the construction of the prototype and pass on this knowledge. These guidelines have been made publicly available, are attached in Appendix C, and were showcased alongside the prototype at Ingenuity 2015.
References


Appendix A

Calculations

A.1 Battery Calculations

Calculations for the LED Africa power systems discussed in Section 2.7. Looking at the minimum battery charge required in Watt hours or Wh:

\[ 5 \text{ Watts} \times 3 \text{ Hours} = 15 \text{ Wh} \]  \hspace{1cm} (A.1)

therefore, the required power output is (assuming 10 hours charging time per day),

\[ \frac{15 \text{ Wh}}{10 \text{ Hours}} = 1.5 \text{ W}. \]  \hspace{1cm} (A.2)

Minimum power requirements compared with capacity of 12V battery is:

\[ \frac{15 \text{ Wh}}{12V} = 1.25 \text{ Ah}. \]  \hspace{1cm} (A.3)

This is approximately \( \frac{1}{50} \) th of the capacity of a standard car battery.

A.2 Design Concept Potential Power Calculations

This section includes sample calculations for all design concepts. These are to be used as a rough guide for comparing the feasibility of design concepts. Many assumptions are made that severely limit the accuracy of the calculations. For example, generator efficiencies are only general estimates. The performance of generators in the prototypes will vary depending on the quality and suitability of those salvaged or bought.

A.2.1 Oscillating Water Column

Assuming that:

- Shore wave conditions are \( f_{\text{wave}} = 1 \text{ Hz}, \rho_{\text{air}} = 1.226 \text{ kg/m}^3, A_{\text{wave}} = 0.1 \text{ m} \)
- Compressibility effects are negligible;
- Wave behaviour is sinusoidal;
- Footprint of OWC width \( b = 3 \text{ m}, \text{ depth } d = 0.3 \text{ m}; \)
- Radius of turbine is \( r = 0.1 \text{ m}; \)
- Turbine performs equally well in both directions;
• Turbine coefficient of performance is $c_{p,turbine} = 0.4$;

• Generator efficiency $n_{generator} = 0.5$.

Now, wave height $H_{wave}$ is a function of time,

$$H_{wave} = 2A_{wave} \sin(2\pi f_{wave} t) = 2 \times 0.1 \text{m} \times \sin(2\pi t).$$

(4.4)

For an OWC we can say that the volume $V$ of displaced air is:

$$V = bdH_{wave} = 3 \text{m} \times 0.3 \text{m} \times (2 \times 0.1 \text{m} \times \sin(2\pi t)) = 0.18 \sin(2\pi t).$$

(5.5)

Differentiating the volume displaced with respect to time gives the volumetric flow rate $Q$.

$$Q = \frac{dV}{dt} = 2\pi \times 0.18 \cos(2\pi t).$$

(6.6)

Then the total power through the turbine $P$ (take absolute value of $Q^3$ as turbine works in both directions) is:

$$P = \frac{1}{2} \rho AU^3 = \frac{1}{2} \rho \frac{|Q^3|}{A^2}$$

(7.7)

Hence, the energy through the chimney produced in 1 second, or the average power in the chimney $P_{ave}$ is,

$$P_{ave} = \int_0^1 P dt = \int_0^1 \frac{1}{2} \rho \frac{|Q^3|}{A^2} dt = \int_0^1 \frac{1}{2} \times 1.226 \times \left| \frac{(2\pi \times 0.18 \cos(2\pi t))^3}{(\pi \times 0.12)} \right| dt = 3.81\text{W}.$$ Considering estimated efficiencies, the total extractable power $P_{ex}$ is:

$$P_{ex} = c_{p,turbine} \times n_{generator} \times P_{ave} = 0.4 \times 0.5 \times 3.81\text{W} = 0.76\text{W}. $$

Charging Capabilities

LED Africa power requirements:

$$15 \text{W h} \approx 20 \text{ hours} \quad \frac{0.76 \text{W}}{}$$

Car battery charging time:

$$840 \text{ W h} \approx 1100 \text{ hours} \quad \frac{0.76 \text{W}}{}$$

Smartphone charging time:

$$5.25 \text{ W h} \approx 7 \text{ hours} \quad \frac{0.76 \text{W}}{}$$
A.2.2 Bicycle Point Absorber

Assuming that:

- Wave conditions are \( f_{\text{wave}} = 1 \) Hz, \( A_{\text{wave}} = 0.25 \) m;
- Buoyancy force on buoy is sufficient to pull hanging mass up to the full height of the wave;
- Hanging mass is \( m = 3 \) kg;
- Generator efficiency is \( n_{\text{generator}} = 0.5 \);
- Drivetrain efficiency is \( n_{\text{drivetrain}} = 0.9 \).

The work done on the hanging mass \( W_{\text{mass}} \) is:

\[
W_{\text{mass}} = E_{\text{potential}} f \\
= 2Afgf \\
= 2 \times 0.25m \times 3kg \times 9.81m/s^2 \times 1Hz \\
= 14.7W.
\]

Considering estimated efficiencies, the total extractable power \( P_{\text{ex}} \) is:

\[
P_{\text{ex}} = n_{\text{generator}} \times n_{\text{drivetrain}} \times W_{\text{mass}} \quad \text{(A.11)}
\]

\[
P_{\text{ex}} = 0.5 \times 0.9 \times 14.7W \\
= 6.6W.
\]

Charging Capabilities

LED Africa power requirements:

\[
\frac{15W}{6.6W} \approx 2.3 \text{ hours} \quad \text{(A.12)}
\]

Car battery charging time:

\[
\frac{840W}{6.6W} \approx 127 \text{ hours} \quad \text{(A.13)}
\]

Smartphone charging time:

\[
\frac{5.25W}{6.6W} \approx 0.8 \text{ hours} \quad \text{(A.14)}
\]

A.2.3 Linear Generator Buoy

Assuming that:

- The magnet takes 0.20 seconds to traverse the solenoid in one direction;
- The magnet takes 0.05 seconds to change direction at each end of the solenoid;
- Maximum magnetic flux \( \Phi_{\text{max}} \) occurs when the magnet is at the midpoint of the solenoid. At this point, the induced magnetic field is uniform across the solenoid;
- When the magnet changes direction at each end of the solenoid, the magnetic field strength across the solenoid is negligible;

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Average change in magnetic flux $\frac{dB}{dt}$ can be fairly approximated linearly over one transverse of the solenoid and one change in direction;

The magnetic field is perpendicular to the solenoid so ($\theta = 0$);

Height of the magnet is $h_{magnet} = 12.7 \times 10^{-3} \text{m}$;

Magnet remnant flux density is $B_{rem} = 1.38 \text{T}$;

Solenoid radius is $r_{solenoid} = 7.50 \times 10^{-3} \text{m}$;

Solenoid height is $h_{solenoid} = 0.10 \text{m}$;

A steel tube of radius, $r_{steel} = 8.00 \times 10^{-3} \text{m}$ surrounds the solenoid;

Magnetic flux loss in the steel tube is negligible;

Number of turns in copper coil, $N = 250$;

Charge controller circuit resistance is $R = 10 \Omega$.

The distance between the steel pipe and the magnet is:

$$d = r_{steel} - r_{magnet}$$

$$= 8.00 \times 10^{-3} \text{m} - 6.35 \times 10^{-3} \text{m}$$

$$= 1.65 \times 10^{-3} \text{m}.$$  \hspace{1cm} (A.15)

The maximum magnetic field strength the solenoid encounters is:

$$B = \frac{h_{magnet}}{h_{magnet} + 2 \times d \times B_{rem}}$$

$$= \frac{12.7 \times 10^{-3} \text{m}}{12.7 \times 10^{-3} \text{m} + 2 \times 1.65 \times 10^{-3} \text{m} \times 1.38 \text{T}}$$

$$= 1.09 \text{T}.$$  \hspace{1cm} (A.16)

Now, the cross sectional area of the solenoid is:

$$A = \pi \times r_{solenoid}^2$$

$$= \pi \times (7.5 \times 10^{-3} \text{m})^2$$

$$= 1.77 \times 10^{-4} \text{m}^2.$$  \hspace{1cm} (A.17)

Then the maximum magnetic flux the solenoid encounters is:

$$\Phi_{max} = B \times A \times \cos(\theta)$$

$$= 1.09 \text{T} \times 1.77 \times 10^{-4} \text{m} \times \cos(0)$$

$$= 1.94 \times 10^{-4} \text{Wb}.$$  \hspace{1cm} (A.18)
**Linear estimate of the change of magnetic flux:**
Consider one period of magnet oscillation. The magnetic flux is negligible when the magnet is at the top of the solenoid, then at a maximum when the magnet is at the middle of the solenoid. Next it is once again negligible when the magnet is at the bottom of the solenoid and maximum at the middle of the solenoid and so on as the magnet oscillates.

So as the magnet falls, $d|\Phi| = 2\Phi_{\text{max}}$ because it goes from zero to maximum, and then back to zero. The same is true as the magnet bounces back up. Absolute value is taken as the voltage will be rectified.

Hence for one oscillation,

$$d|\Phi| = 2\Phi_{\text{max}} + 2\Phi_{\text{max}} + 0 \quad \text{(A.19)}$$

and for the same period of oscillation,

$$dt = 2 \times t_{\text{transverse}} + 2 \times t_{\text{changedirection}}$$

$$= 2 \times 0.20s + 2 \times 0.05s$$

$$= 0.50s.$$  \hspace{1cm} \text{(A.20)}

Therefore, the change in magnetic flux is:

$$\frac{d|\Phi|}{dt} = \frac{7.76 \times 10^{-4}\text{Wb}}{0.50s}$$

$$= 1.55 \times 10^{-3}\text{Wb/s}. \quad \text{(A.21)}$$

Calculating the average induced emf (as the magnetic field is averaged, and the output is rectified),

$$\epsilon = -N \frac{d\Phi}{dt} \quad \text{(A.22)}$$

$$= 500 \times 1.55 \times 10^{-3}\text{Wb/s}$$

$$= 0.776V.$$  \hspace{1cm} \text{(A.22)}

Power output: Assuming a charge controller circuit resistance of 10$\Omega$ is,

$$P = \frac{V^2}{R} \quad \text{(A.23)}$$

$$= \frac{(0.776V)^2}{10\Omega}$$

$$= 0.0602W.$$  \hspace{1cm} \text{(A.23)}

**Charging Capabilities**

LED Africa power requirements:

$$\frac{15\text{Wh}}{0.0602W} \simeq 249 \text{ hours} \quad \text{(A.24)}$$

Car battery charging time:

$$\frac{840\text{Wh}}{0.0602W} \simeq 14000 \text{ hours} \quad \text{(A.25)}$$
Smartphone charging time: \[
\frac{5.25 \text{Wh}}{0.0602 \text{W}} \approx 87 \text{ hours} \quad (A.26)
\]

Potentially, if an array of 10 linear generator buoys was constructed, then the charging time for a smartphone becomes:
\[
\frac{5.25 \text{Wh}}{10 \times 0.0602 \text{W}} \approx 8.7 \text{ hours} \quad (A.27)
\]

### A.2.4 On-shore Tapered Wave Channel

Assuming that:
- Wave conditions are \( f_{\text{wave}} = 0.5 \) Hz, \( \rho_{\text{seawater}} = 1027 \text{ kg/m}^3 \);
- The amplitude of waves is sufficient enough such that the reservoir completely fills for every period (min \( A = 0.15 \text{m} \));
- The reservoir has square footprint of width \( w = \text{breadth} b = 2 \text{m} \);
- The reservoir cross section is triangular. Maximum water head \( H_{\text{max}} = 0.3 \text{ m} \);
- The average water head is 0.26 m (found by iteration);
- The turbine has a coefficient of performance \( c_{p,\text{turbine}} = 0.4 \);
- The generator efficiency is \( n_{\text{generator}} = 0.5 \).

Finding the volumetric flow rate,
\[
Q = A \sqrt{2gH_{\text{ave}}} \quad (A.28)
\]
\[
= (\pi \times 0.12)^2 \times 0.071 \text{m}^3/\text{s}.
\]

Calculating the average power output (if the turbine is continually spun, at an average water height),
\[
P_{\text{ave}} = \dot{m}gH_{\text{ave}} \quad (A.29)
\]
\[
= \rho QgH_{\text{ave}} \quad (A.30)
\]
\[
= 1027\text{kg/m}^3 \times 0.071\text{m}^3/\text{s} \times 9.81\text{m/s}^2 \times 0.26\text{m}
\]
\[
= 186.0\text{W}.
\]

Considering estimated efficiencies, the total extractable power \( P_{\text{ex}} \) is:
\[
P_{\text{ex}} = c_{p,\text{turbine}} \times n_{\text{generator}} \times P_{\text{ave}} \quad (A.31)
\]
\[
= 0.4 \times 0.5 \times 186.0\text{W}
\]
\[
= 37.2\text{W}.
\]

### Charging Capabilities

LED Africa power requirements:
\[
\frac{15\text{Wh}}{37.2\text{W}} \approx 0.4 \text{ hours} \quad (A.32)
\]
A.2 Design Concept Potential Power Calculations

Car battery charging time:
\[
\frac{840\text{Wh}}{37.2\text{W}} \approx 22.6 \text{ hours} \quad \text{(A.33)}
\]

Smartphone charging time:
\[
\frac{5.25\text{Wh}}{37.2\text{W}} \approx 0.14 \text{ hours} \quad \text{(A.34)}
\]
Appendix B

Management

From the beginning of the year and as major milestones completed, the project has been continually managed to ensure of a timely completion and constantly examined to guarantee the aims were met. Throughout the year the Gantt chart has been followed as closely as possible, however some processes such as construction were delayed, these delays were managed which allowed for the success in completing the project. Risk and safety assessments were made early on to reduce the chance of failure and budget was followed to keep the project within the scope. The general step by step process for the year was evaluated in the work breakdowns structure on a failure basis to aid in project management.

B.1 Project Goals

The project goals as specified in the Project Charter remain unchanged. They are included below, and were completed as detailed in Section 9.2.

To design a range of self-sufficient, corrosion resistant wave energy converter systems (up to three), that can be built predominantly using repurposed scrap materials, and function continuously in high and low tide. The design output of these systems will be sufficient to provide a range of remote, developing communities with their minimum domestic power requirements. The systems will be designed by the honours team; however the knowledge, ideas and feedback of advisers such as Dr Birzer and other engineers will have an influence. The design of a system that meets the necessary output will be considered a success, and it is believed that this is achievable in the provided timeframe with the resources available. The designs should be detailed in the preliminary report; however they may still be adjusted during the prototype testing phase (reflecting the iterative nature of engineering design).

To source materials, construct and test the designed prototypes. Since sourcing materials, construction and testing are co-dependent outcomes, success will be measured by successfully testing and gathering data in the wave chamber, and successful in-field testing. These tasks will be performed by the honours team, with some assistance. Construction will be attempted without external help, however the staff of the Mechanical Engineering workshop may be asked to perform some minor tasks beyond the capabilities of the honours team. The assistance of the University of Adelaide’s workshop staff will be needed to operate the wave flume safely and effectively. This goal is achievable in the provided timeframe and with the resources available. This goal is scheduled to be completed during the semester break (July).

To create guidelines for the construction of wave energy converter systems that are clear to understand for an unskilled audience, and adaptable to a wide variety of conditions and
available materials. The guidelines must be detailed enough for an unaffiliated and largely unskilled person to read and understand the methods for building wave energy converters from scrap materials. The extent of the guidelines will be determined by the nature of the project designs. The guidelines will be created by the honours team, with advice from Dr Birzer. The goal is achievable - all necessary resources are available and there is sufficient time. The guidelines will be completed in time for presentation at Ingenuity (October 26-27).

B.2 Gantt Chart

The Gantt Chart in Figure B.1 has been updated to reflect the final construction timeline and requirements of the prototype. Significant changes to the Gantt chart as per June 2015 (Figure B.2) are detailed below.

- Scrapyard visit deemed unnecessary - scrapyards were contacted to explore the possibility of foraging for scrap in person. Due to safety and insurance issues, this possibility was not welcomed by the scrapyard operators. Significant scrap materials were found on the “Freebies” section of Gumtree, and so further inquiries to scrapyards were deemed unnecessary.

- Safety Inductions for working in the Civil Engineering Lab - In order to use the Wave Flume in the School of Civil, Environmental and Mining Engineering Lab, three safety inductions needed to be completed. These were “Chemical Management” and “Hazard Management” courses, and an induction into the safe use of the wave flume. These were completed in late May/early June.

- Tom Heinrich Overseas - The opportunity arose for Tom to travel to Cambodia with Engineers Without Borders for a Humanitarian Design Summit. Therefore, he was unable to contribute to the project for 3.5 weeks in July. Consequently, some parts of construction and prototyping were pushed to August and September.

- Dr Cristian Birzer Overseas - Dr Birzer took a two month overseas placement through August and September. During this time he was readily available for email correspondence, but unavailable for face-to-face meetings. In his absence, weekly meetings were had with Dr Erwin Gamboa, and the minutes attached to an update email each week to Dr Birzer.

- Second wave flume test was deemed unnecessary - Although the wave flume was used sporadically to test different components, only one formal, data collecting test was required. This was due to the range of conditions the wave flume could simulate not aligning with the operating range of the prototype, as discussed in Section 8.1.

- Other minor changes were made to the dates of each tasks for a variety of reasons such as the availability of team members, availability of resources, and field wave conditions. All tasks are listed as complete, except distributing the guidelines which is due for completion in early November.
1976 - Wave Power from Repurp...

Deliverables
- Project Charter
- Project Charter Draft Complete
- Project Charter Final Complete
- IP Forms Due
- Preliminary Report
- Preliminary Report Draft Complete
- Preliminary Report Final Complete
- Final Report
- Final Report Draft Complete
- Final Report Complete
- Guidelines
- Ingenuity Preparation and Poster
- Ingenuity
- Distribute Guidelines

 Prototype Construction and Testing
- Bicycle Final Design Review
- Purchase Remaining Bicycle System Materials
- Experimenting with Motors and Generators for Bicycle system
- Bicycle Ocean-land Power Transfer Subsystem Construction
- Bicycle Linear to Rotational Motion Drivetrain Subsystem Construction
- Bicycle Rotational Motion to Generator Subsystem Construction
- Unsuccessful Construction Attempts
- Optimised Linear Gen Final Design Review
- Purchase Magnet and Elastic
- Optimised linear Gen Construction
- Linear Gen from Scrap Final Design Review
- Linear Gen from Scrap Construction
- Prototype Modifications and Testing Iterations
- Wave Flume Induction
- First Test (Wave Flume)
- First Wave Flume Test Data Analysis
- First Field Test
- First Field Test Data Analysis
- Second Field Test

Figure B.1: Updated Gantt chart page one.
Figure B.2: Updated Gantt chart page two.
Figure B.3: Gantt chart as per June 2015.
B.3 Work Breakdown Structure

The work breakdown structure (WBS) includes two categories of milestones, these being deliverables and prototype tasks. The deliverables refer to all of the University of Adelaide requirements, reports, final guidelines and Ingenuity 2015. The prototype tasks refers to both concept designs from initial design review to final prototype construction and the data collections and analysis. The WBS is colour coded to reflect the completion of each task. As all goals and deliverables were achieved successfully, all entries of the WBS are green.

Table B.1: Traffic light assessment.

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Description</th>
<th>Status</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Preliminary report and design development</td>
<td>Green</td>
<td>All risks have been successfully managed. Expected to be completed on time.</td>
</tr>
<tr>
<td>2</td>
<td>Prototype final design reviews</td>
<td>Green</td>
<td>All risks have been successfully managed. Expected to be completed on time.</td>
</tr>
<tr>
<td>3</td>
<td>Prototype construction</td>
<td>Green</td>
<td>While some delays occurred as a result of sourcing materials, construction was completed within the required time.</td>
</tr>
<tr>
<td>4</td>
<td>Laboratory testing (CEME wave flume)</td>
<td>Green</td>
<td>Communication with staff at the wave flume and other users was handled smoothly and all testing was completed on schedule.</td>
</tr>
<tr>
<td>5</td>
<td>Field testing</td>
<td>Green</td>
<td>All risks have been successfully managed. Some issues arose as a result of inconsistent weather and reliance on online surf reports. However, field testing was completed within an adequate timeframe.</td>
</tr>
<tr>
<td>6</td>
<td>Data analysis</td>
<td>Green</td>
<td>All risks have been successfully managed. Completed on time.</td>
</tr>
<tr>
<td>7</td>
<td>Guidelines</td>
<td>Green</td>
<td>As good results were gathered, guidelines have been completed on time for Ingenuity.</td>
</tr>
<tr>
<td>8</td>
<td>Ingenuity and poster</td>
<td>Green</td>
<td>All risks have been successfully managed. Completed on time.</td>
</tr>
<tr>
<td>9</td>
<td>Final report</td>
<td>Green</td>
<td>All risk have been successfully managed. Expected to be completed on time.</td>
</tr>
</tbody>
</table>
B.4 Risk and Safety Assessment

The risk assessment from the preliminary report has been included in Table B.2. At the time, lack of technical experience, corrosion issues and data loss were deemed to be the most significant risks. A lack of technical expertise did not stop the successful achievement of project goals. Corrosion was identified as a significant risk to the project. The bicycle point absorber prototype was designed to minimise corrosion issues by keeping all corrodi-
ble parts away from the water, but the prototype still operates in a humid environment. Testing the prototype in-field for an extended period (several days, possibly weeks) would have given a better indication of the susceptibility to corrosion. Based upon this, there is no evidence to suggest that corrosion was successfully managed, or caused the prototype to wear out unsatisfactorily quickly. The risk of data loss was mitigated by the use of cloud storage (Dropbox) which was automatically backed up onto all team members’ computers. There were no instances of data loss in the lifetime of the project.

The safety assessments were generated using the Risk Management and Safety Systems (RMSS) program. Use of tools for construction, moving parts in the system, electricity being produced and battery handling all had inherent risks, however the overall safety risks were quite low and appropriate measures to mitigate risk were implemented as necessary. Team members and other personnel were made aware of the safety risks prior to working on the project. During the entirety of the project, no failures occurred. A more in-depth discussion for each risk is given below before the RMSS solutions.

- Moving and sharp parts:
  The waves will cause movement in the ropes, spools, bicycle pedals, chain and back wheel. Therefore appropriate space must be kept between personnel and moving parts. Gloves may be worn as appropriate when dealing with moving parts. To stop the back wheel quickly, the brakes on the bike handle can be used. To stop electricity being produced, the tensioning spring can be removed so that no contact exists between the wheel and generator. During Ingenuity the pedal will be cranked by attendees to power a light, all other moving parts will be given some clear space so that there is minimal risk of injury.

- Water:
  As electricity is being produced, it is very important that water does not come in contact with any of the electrical systems. As the generator and electrical components were elevated, there was no risk of them coming in contact with water. As no shield was constructed to stop rain from making contact with the system, no field testing was done on rainy days.

- Electricity:
  Due to the potential for high voltage output from the generator, all electrical devices must be insulated properly. When working on the electrical system the generator must be disconnected from the back wheel so that no power is generated. As a capacitor is used in parallel with the battery, the capacitor must be discharged with resistors after testing has concluded. For Ingenuity, no electrical components will be in contact range of attendees, with a light bulb being a visual representative of generated power.

- Battery:
  If the charge controller fails and incorrect voltage is applied to the battery there is
a chance that the battery may fail. Depending on the type of battery, this may be hazardous. The battery was placed into its own separate container so that leaks are isolated.
### Table B.2: Risk matrix

<table>
<thead>
<tr>
<th>Item</th>
<th>Likelihood</th>
<th>Severity</th>
<th>Risk</th>
<th>Mitigation Strategies</th>
<th>New Likelihood</th>
<th>New Severity</th>
<th>New Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of technical expertise within the team resulting in an inability to put ideas and designs into real-world practice.</td>
<td>Likely</td>
<td>Significant</td>
<td>High</td>
<td>Draw on information from previous designs and on the knowledge and expertise of the various people who can assist at the University of Adelaide.</td>
<td>Possible</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Inability to adequately deal with corrosion issues when using repurposed scrap material.</td>
<td>Likely</td>
<td>Significant</td>
<td>High</td>
<td>Limit or exclude any metal to metal contact, use polymers when in contact with water, ensure that either the corroding parts can be easily replaced or design such that any parts with corrosion are insignificant.</td>
<td>Likely</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Data loss in the event of corruption or loss of physical copies.</td>
<td>Possible</td>
<td>Significant</td>
<td>Medium-High</td>
<td>Keep multiple copies of files, minimum two, and utilise cloud storage.</td>
<td>Unlikely</td>
<td>Significant</td>
<td>Low</td>
</tr>
<tr>
<td>Lack of time to fully complete project if a team member falls ill and is unable to carry on work.</td>
<td>Possible</td>
<td>Moderate</td>
<td>Medium</td>
<td>Look after team members and ensure that time is managed appropriately for work and time off.</td>
<td>Unlikely</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Risk of uncooperative Non-Government Organisations used as a point of contact on the ground in chosen locations where information is required by the team regarding needs and availability of material or suitability of location.</td>
<td>Possible</td>
<td>Moderate</td>
<td>Medium</td>
<td>Adequately prepare documents when making contact with NGOs to ensure that our goals and requirements are clear and realistic.</td>
<td>Unlikely</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Lack of suitable scrap material to make building a prototype feasible.</td>
<td>Possible</td>
<td>Moderate</td>
<td>Medium</td>
<td>Investigate solutions from previous Honours Projects where scrap material was used and or integrate off-the-shelf components where necessary</td>
<td>Unlikely</td>
<td>Minor</td>
<td>Low</td>
</tr>
<tr>
<td>Item</td>
<td>Likelihood</td>
<td>Severity</td>
<td>Risk</td>
<td>Mitigation Strategies</td>
<td>New Likelihood</td>
<td>New Severity</td>
<td>New Risk</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
<td>----------</td>
<td>------</td>
<td>-----------------------</td>
<td>----------------</td>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>Lack of technological development in wave energy converter technology with regards to available information such that we can reverse engineer current models or systems.</td>
<td>Unlikely</td>
<td>Moderate</td>
<td>Medium</td>
<td>Design a simple system which maximises the likelihood of reaching our goals such that a sufficient level of energy is produced</td>
<td>Unlikely</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Inter-team complications where there may be disagreement between team members escalating to project sabotage.</td>
<td>Unlikely</td>
<td>Moderate</td>
<td>Medium</td>
<td>Ensure that any complications within the team are dealt with quickly and effectively such that work can continue. Organise time outside of the project for the team to relax in an extracurricular activity.</td>
<td>Unlikely</td>
<td>Minor</td>
<td>Low</td>
</tr>
<tr>
<td>Lack of funding in the event that either scrap material is not suitable or that the scrap material is more expensive than initially costed.</td>
<td>Unlikely</td>
<td>Minor</td>
<td>Low</td>
<td>Broaden scrapyard search or consider and investigate sponsorship.</td>
<td>Unlikely</td>
<td>Minor</td>
<td>Low</td>
</tr>
</tbody>
</table>
# Risk Register

**Location**: The University of Adelaide - Fac of Eng, Comp & Math Sci - School of Mechanical Eng - *N/A - North Terrace - *N/A - *Level 3 - *N/A - 1976: Wave Power From Scrap Material

**Master Category**: OHS

---

<table>
<thead>
<tr>
<th><strong>Assessment Type</strong></th>
<th><strong>Tasks</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assessment Checklist</strong></td>
<td><strong>Tasks - General</strong></td>
</tr>
</tbody>
</table>

**Entity**: The University of Adelaide

**School/Branch**: School of Mechanical Eng

**Campus**: North Terrace

**Room**: *Level 3

**Building**: *N/A

**Room Type**: *N/A

**Risk Assessment Title**: 1976: Wave Power From Scrap Material

---

## Assessment Record: 2796

**Assessment Checklist**: OHS - Tasks - General

### ID | Hazard | Hazard Description/Nature of Risk | How can this hazard/threat cause an incident/adverse event? | Residual | Assessor

| 13975 | Contact with chemicals, fumes or gas | Is there the potential for a person to come into contact with chemicals or gas? e.g., fumes from chemicals, dry ice, machine oils, Liquid N2 | Batteries contain acid and alkaline chemicals which can cause harm when people come in contact with it. | Low (6) | Patrick Jan Wick

---

**Risk Assessment Keywords**

What controls are currently in place?

- Identifying battery leaks and having latex gloves available for handling batteries.

---

**ID** | **Action Description** | **Control Statement** | **Responsible Person** | **Due Date** | **Cost** | **Progress** | **Control Type**

---

(Printed 22 May 2015 2:09:23 PM) Printed copies are uncontrolled
All wiring will be insulated and all electrical components will be waterproofed.

### Risk Assessment Keywords

- Patrick Jan Wick
- Low (6)

All system designs will create electricity and use batteries which can cause shock if not properly wired.

<table>
<thead>
<tr>
<th>ID</th>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13976</td>
<td>Contact with electricity or potential for electric shock</td>
<td>Is there the potential for a person to come into contact with live electricity or receive an electric shock? e.g. Overhead or underground power lines, exposed wires, water near equipment, leads/switch in poor condition</td>
<td>All system designs will create electricity and use batteries which can cause shock if not properly wired</td>
<td>Low (6)</td>
<td>Patrick Jan Wick</td>
</tr>
</tbody>
</table>

**Risk Assessment Keywords**

- Contact with electricity or potential for electric shock
- What controls are currently in place?

All wiring will be insulated and all electrical components will be waterproofed.
B.4 Risk and Safety Assessment

Low frictional material cords will be used as a first priority and gloves will be used when handling the cord.

What controls are currently in place?

Low frictional material cords will be used as a first priority and gloves will be used when handling the cord.

<table>
<thead>
<tr>
<th>ID</th>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13977</td>
<td>Contact with hot object or friction burn</td>
<td>Is there the potential for a person to come into contact with an object which is hotter than 50 degrees Celsius? e.g. steam, naked flame, laser beams, heating block</td>
<td>One concept design has a cord of some material that links the wave movement to a drive chain, contact with the cord may cause frictional burn with strong wave movement.</td>
<td>Low (4)</td>
<td>Patrick Jan Wicik</td>
</tr>
</tbody>
</table>

Risk Assessment Keywords

- Low (4)

---

### Table

<table>
<thead>
<tr>
<th>ID</th>
<th>Action Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost</th>
<th>Progress</th>
<th>Control Type</th>
</tr>
</thead>
</table>

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<thead>
<tr>
<th>ID</th>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13978</td>
<td>Contact with sharp object</td>
<td>Is there the potential for a person to be cut, stabbed or punctured by a sharp object? e.g., knife, sharp or pointy edge objects, flying or moving objects</td>
<td>Use of knives, saws and drills are necessary for construction and have the potential to wound people.</td>
<td>Low (4)</td>
<td>Patrick Jan Wick</td>
</tr>
</tbody>
</table>

Risk Assessment Keywords

What controls are currently in place?

Safety equipment such as gloves, long sleeve clothing and safety glasses worn for use of saws and drills. Cutting away from the body for use of tools. Stabilising items to a bench when being worked on.
### Risk Assessment Keywords

**Patrick Jan Wicik**

- Low (4)

Bicycle gear train can capture clothing, accessories, hair or skin when in contact

<table>
<thead>
<tr>
<th>ID</th>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13979</td>
<td>Entangled on moving machinery</td>
<td>Is there the potential for a person to be entangled on moving parts of a machine? e.g. hair,</td>
<td>Bicycle gear train can capture clothing, accessories,</td>
<td>Low (4)</td>
<td>Patrick Jan Wicik</td>
</tr>
<tr>
<td></td>
<td></td>
<td>jewellery, clothing, cleaning aids, gloves</td>
<td>hair or skin when in contact</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Risk Assessment Keywords

- What controls are currently in place?

Wearing tight clothing, no accessories and keeping a safe distance of approximately 0.3m away from moving machinery parts.
<table>
<thead>
<tr>
<th>ID</th>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13980</td>
<td>Explosion / Fire hazards</td>
<td>Is there a potential for a person to be injured by an explosion or fire? e.g., ignition of surrounding area, using naked flame, gas, vapour, grain silos, chemical incompatibility, shock sensitive chemicals, chemical stability</td>
<td>Incorrect electrical inputs for a battery can cause the battery to leak or explode.</td>
<td>Low (6)</td>
<td>Patrick Jan Wicik</td>
</tr>
</tbody>
</table>

**Risk Assessment Keywords**

- Identifying safe electrical inputs for different batteries used and testing inputs with data loggers before attaching a battery.
### B.4 Risk and Safety Assessment

Wearing proper footwear and being aware of uneven surfaces and wet surfaces

#### Risk Assessment Keywords

- Patrick Jan Wicik
- Low (4)
- Wave energy converters will be placed in and next to water, the wet surface increase changes for slipping.

### Is there the potential for a person to slip, trip or fall?

- e.g. slippery, uneven or cluttered work surfaces, plant location, lack of safe guards such as rails

### Slips, Trips or Falls

<table>
<thead>
<tr>
<th>ID</th>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13981</td>
<td>Slips, trips or falls</td>
<td>Is there the potential for a person to slip, trip or fall?</td>
<td>Wave energy converters will be placed in and next to water, the wet surface increase changes for slipping.</td>
<td>Low (4)</td>
<td>Patrick Jan Wicik</td>
</tr>
</tbody>
</table>

#### Risk Assessment Keywords

- What controls are currently in place?
- Wearing proper footwear and being aware of uneven surfaces and wet surfaces
Suspended mass will be constrained to vertical movement and all personnel will remain a safe distance away from the working system.

Risk Assessment Keywords

<table>
<thead>
<tr>
<th>ID</th>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13982</td>
<td>Struck by moving object</td>
<td>Is there the potential for a person to be struck by a moving object? (This excludes vehicles)</td>
<td>Moving suspended mass will have enough momentum to cause injury such as bruises or potential fractures when it comes in contact with a person.</td>
<td>Low (6)</td>
<td>Patrick Jan Wick</td>
</tr>
</tbody>
</table>

**Risk Assessment Keywords**

What controls are currently in place?

Suspended mass will be constrained to vertical movement and all personnel will remain a safe distance away from the working system.

<table>
<thead>
<tr>
<th>ID</th>
<th>Action Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost</th>
<th>Progress</th>
<th>Control Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
B.5 Budget

Given that the project was constructed using repurposed materials, costs have been minimised for many necessary components. In certain cases where items could have been found as scrap material, they have been purchased to save time and to guarantee that they are fully functional. To date, as most materials have been salvaged from scrap materials the total budget has totalled $622.93 for materials and $54,600 salary. In order to ensure that the designs could be built by remote communities, construction was completed by team members outside of a workshop environment wherever possible.

The entire year’s spending is shown in the table below, with an asterisk next to the materials that were used in the final bicycle point absorber prototype. Many materials were used for discontinued prototypes or were necessary tools for construction and testing.

<table>
<thead>
<tr>
<th>Date</th>
<th>Supplier</th>
<th>Item</th>
<th>Quantity</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr 18</td>
<td>BP</td>
<td>Rubber bands</td>
<td>1 bag</td>
<td>2.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Super glue</td>
<td>1</td>
<td>5.99</td>
</tr>
<tr>
<td>Apr 22</td>
<td>Mitre 10</td>
<td>PVC pipe 75mm</td>
<td>1m</td>
<td>4.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PVC pipe 90mm</td>
<td>1m</td>
<td>4.49</td>
</tr>
<tr>
<td>Jun 14</td>
<td>K Mart</td>
<td>Knitted elastic</td>
<td>1</td>
<td>2.50*</td>
</tr>
<tr>
<td>Jun 21</td>
<td>Gumtree</td>
<td>Bicycle</td>
<td>1</td>
<td>30.00*</td>
</tr>
<tr>
<td>Jul 4</td>
<td>Gumtree</td>
<td>Ceiling Fan</td>
<td>2</td>
<td>10.00*</td>
</tr>
<tr>
<td>Jul 17</td>
<td>GHE Lifting</td>
<td>Rare earth disc magnets</td>
<td>18</td>
<td>36.00*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rare earth disc magnets</td>
<td>2</td>
<td>34.91</td>
</tr>
<tr>
<td></td>
<td>Mitre 10</td>
<td>PVC cap 50mm</td>
<td>2</td>
<td>4.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Super glue</td>
<td>1</td>
<td>2.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PVC pipe 25mm</td>
<td>1</td>
<td>4.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PVC pipe 50mm</td>
<td>1</td>
<td>8.54</td>
</tr>
<tr>
<td>Jul 21</td>
<td>Aztronics</td>
<td>Wire 24/20 Red</td>
<td>4m</td>
<td>1.60*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wire 24/20 Black</td>
<td>4m</td>
<td>1.60*</td>
</tr>
<tr>
<td></td>
<td>Mitre 10</td>
<td>Discs round white 10mm</td>
<td>1</td>
<td>7.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tip chair rubber round 10mm</td>
<td>4</td>
<td>1.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tip chair rubber round 6mm</td>
<td>4</td>
<td>0.99</td>
</tr>
<tr>
<td>Aug 15</td>
<td>Mitre 10</td>
<td>Pine board 70mm x 19mm</td>
<td>4.5m</td>
<td>10.36*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pine board 70mm x 35mm</td>
<td>1.2m</td>
<td>3.59*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10-8 x 65 chipboard screws</td>
<td>16 pack</td>
<td>3.14*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8-10 x 35 chipboard screws</td>
<td>30 pack</td>
<td>3.59*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hoop iron (0.8×30mm)</td>
<td>6m</td>
<td>6.64*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bolt hex $\frac{1}{4}$&quot;</td>
<td>2</td>
<td>0.40*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Washer $\frac{3}{4}$&quot;</td>
<td>8</td>
<td>0.22*</td>
</tr>
<tr>
<td>Aug 17</td>
<td>K Mart</td>
<td>Hand fishing reel</td>
<td>2</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>Mitre 10</td>
<td>Cable ties</td>
<td>500 pack</td>
<td>6.00*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pine board 70mm x 19mm</td>
<td>2.7m</td>
<td>6.72*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rope poly 3mm</td>
<td>20m</td>
<td>9.00*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bolt cup $\frac{3}{4}$&quot;</td>
<td>1</td>
<td>1.20*</td>
</tr>
<tr>
<td></td>
<td>Aztronics</td>
<td>16A 100V Schottky rectifier</td>
<td>6</td>
<td>19.80</td>
</tr>
</tbody>
</table>
For all bicycle point absorber materials, the cost could be reduced further to an estimated $100 by being stricter on the use of repurposed materials. Items such as the bicycle, hoop iron, battery, nuts and bolts, springs and ceiling fans could be found as scrap material. Materials that were still deemed necessary to purchase are the rare earth magnets and solar charge controller. Although these can be found and constructed through repurposed materials, the quality would be significantly reduced.

A Wattsview data logging system (~$350) and a soldering iron (~$50) were provided in-kind by the University of Adelaide for the duration of the project. Two multimeters

---

<table>
<thead>
<tr>
<th>Date</th>
<th>Supplier</th>
<th>Description</th>
<th>Quantity</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 18</td>
<td>Gotcha Fishing</td>
<td>Lead set universal test</td>
<td>1</td>
<td>8.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hand caster</td>
<td>2</td>
<td>7.20*</td>
</tr>
<tr>
<td>Aug 21</td>
<td>GHE Lifting</td>
<td>Rare earth disc magnets</td>
<td>15</td>
<td>30.00*</td>
</tr>
<tr>
<td>Aug 22</td>
<td>Mitre 10</td>
<td>8-10 x 40 chipboard screws</td>
<td>28 pack</td>
<td>3.19*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Super glue</td>
<td>2</td>
<td>2.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adhesive araldite 24ml</td>
<td>1</td>
<td>12.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spring extension 11.913 × 114.2 × 1.041mm</td>
<td>1</td>
<td>19.98*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hoop iron (0.8×30mm)</td>
<td>6m</td>
<td>7.99*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bolt cup 1/4”</td>
<td>5</td>
<td>1.69*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bolt cup 3/8”</td>
<td>1</td>
<td>1.20*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pine board 70mm x 19mm</td>
<td>2.4m</td>
<td>5.98*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Staple galvanised 2mm</td>
<td>1</td>
<td>3.49*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nut hex 1/4”</td>
<td>17</td>
<td>0.85*</td>
</tr>
<tr>
<td>Aug 26</td>
<td>Jaycar</td>
<td>Bridge rectifier 400V 6A</td>
<td>2</td>
<td>5.00*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wire 24/20 Red</td>
<td>4m</td>
<td>2.00*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wire 24/20 Black</td>
<td>4m</td>
<td>2.00*</td>
</tr>
<tr>
<td>Aug 28</td>
<td>Jaycar</td>
<td>12V lead acid battery charger</td>
<td>1</td>
<td>24.95</td>
</tr>
<tr>
<td>Sep 8</td>
<td>Jaycar</td>
<td>Crimp tool</td>
<td>1</td>
<td>14.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cable connectors</td>
<td>16 pairs</td>
<td>14.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrical tape</td>
<td>1</td>
<td>0.85</td>
</tr>
<tr>
<td>Sep 11</td>
<td>Jaycar</td>
<td>Alligator Clips</td>
<td>10</td>
<td>6.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar charge controller (12v)</td>
<td>1</td>
<td>29.95*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5W resistor</td>
<td>4</td>
<td>1.92</td>
</tr>
<tr>
<td>Sep 15</td>
<td>Mitre 10</td>
<td>Hoop iron (0.8×30mm)</td>
<td>30m</td>
<td>26.99*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gloves</td>
<td>1</td>
<td>19.99</td>
</tr>
<tr>
<td>Sep 20</td>
<td>Geddes &amp; George</td>
<td>Screw driver kit</td>
<td>1</td>
<td>4.25</td>
</tr>
<tr>
<td>Oct 5</td>
<td>Mitre 10</td>
<td>Socket set</td>
<td>1</td>
<td>39.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Duct tape</td>
<td>30m</td>
<td>3.99*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blade Hacksaw 3 piece</td>
<td>1</td>
<td>6.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Safety Glasses</td>
<td>1</td>
<td>9.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WD40 Lubricant</td>
<td>1</td>
<td>11.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Socket Adapter</td>
<td>1</td>
<td>14.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ratchet</td>
<td>1</td>
<td>14.99</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>622.93</td>
</tr>
<tr>
<td>*<em>Total</em></td>
<td></td>
<td></td>
<td></td>
<td>251.56</td>
</tr>
</tbody>
</table>
were provided by the students for testing and verification.

Since the project has begun, each team member has averaged 13 weekly hours, totalling 468 labour hours. This is an average of the hours and cost of labour as the amount of hours spent on the project varies week to week, increasing particularly near deadlines. Subtracting two weeks for semester one SWOTVAC and the examination period, the project has a total lifetime of 28 weeks. At a rate of $50/hr, this amounts to $1950/week or $54,600 in total.

The total budget for the entire project:

$622.93 of purchased materials, $400 in-kind equipment and $54,600 salary.

B.6 Summary

All deliverables have been met and prototype construction was completed in time for testing and data collection to be obtained. Revisions to the goals and scope of the project were not deemed necessary. The updated Gantt chart shows the timeframe for all tasks and the Gantt chart as per June 2015 is included to highlight changes. A description of major milestones and an assessment are included in the WBS. No milestones were at any significant risk. In summary, all aspects of the project were completed satisfactorily.
Appendix C

Guidelines

The following page begins the Guidelines for the Construction of a Wave Energy Converter from Repurposed Materials as one of the important deliverables of the project. The guidelines are designed to be a starting base of recommendations for the construction of a WEC from repurposed materials and are not by all means the only solution. As highlighted in the Introduction, Section 1.2, there is a vast number of very different designs of WEC. Therefore, the guidelines present our one possible solution.
Guidelines for the Construction of a Wave Energy Converter from Repurposed Materials

Heinrich, T., Sebi, A. & Wicik, P.

With assistance from Birzer, C. & Gamboa, E.

The University of Adelaide

Disclaimer:
The authors, supervisors and the University of Adelaide do not take responsibility for damage or injury resulting from the manufacturing or operation of any device produced as a result of using these guidelines. Alteration to existing equipment may void warranties or guarantees.
Executive Summary

These guidelines are a set of recommendations for the construction of a wave energy converter from predominantly repurposed and cheaply purchased materials. The wave energy converter produces electricity from the motion of ocean waves and stores it in a battery. The guidelines are based upon the prototyping efforts of honours students at The University of Adelaide. Figure 1 shows the constructed prototype with identified subsections. Sections in this report explain the role of each subsystem, how it was constructed, challenges that should be considered, and ideas for alternative construction materials and methods.

In the design of a wave energy converter from these guidelines, each subsystem should be considered and analysed for suitability with other subsystems and options to find the most effective solution.

Figure 1- Bicycle Point Absorber Full System
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  Buoy and Counter Weight Guidelines: .................................................................................. 27
  Back Wheel Flywheel Construction: .................................................................................... 28
  Wooden Frame Construction: .............................................................................................. 29
  Charge Controller System: ..................................................................................................... 30
Section 1: Wave Energy Converter Concept

Introduction:
As shown in Figure 1, Subsystem 1 includes a buoy that is worked by the motion of the ocean waves. The use of cables, the pulley system and the counter-weight converts this linear motion into rotational motion within a bicycle drivetrain, as this provides a commonplace and cost-efficient method for unidirectional rotation with smooth bearings. Subsystem 2 includes gearing that can optimise the power output of the system under given wave conditions, and the generator which converts the rotational motion into electricity. Subsystem 3 is purely electrical and converts the output of the generator into a suitable voltage and direct current that is suitable for storage, and converts this to chemical energy stored in the battery.

Is a Wave Energy Converter Suitable?
The exact power output of a wave energy converter varies greatly upon the design and build of each individual subsystem and the available power for the wave conditions at hand. In the constructed prototype, it is estimated that for wave conditions of 0.8-1.0m height and one wave per three seconds an average power output of 1 Watt could be achieved. This is enough power to charge a regular phone battery in 4-5 hours. Based on the performance of this prototype, Table 1 shows the power output that can be expected for different wave conditions. The design of this prototype assumes the use of a suitable jetty, pier or any appropriately raised location.

Table 1- Power Expectations for Given Wave Conditions (W)

<table>
<thead>
<tr>
<th>Wave height (m)</th>
<th>Waves per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>0.75</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.25</td>
<td>2</td>
</tr>
<tr>
<td>1.5</td>
<td>4</td>
</tr>
</tbody>
</table>
Subsystem 1 absorbs the kinetic energy of the ocean waves converting it to rotational kinetic energy in the drivetrain. A buoy sits on the ocean surface where it floats up when met with a wave, and allowed to fall with the trough of the wave. In the case of the prototype built in 2015 by the Honours team, the buoy was made from 3L milk containers tied together, each approximately half full of water (Figure 3). The weight of the buoy is an important aspect of the system as it determines the force with which the system is driven. It must be heavy enough such that there is sufficient torque in the system to produce a fast rotation of the system but at the same time light enough so that it is manageable for the user and is able to float on the surface of the water. There is room for experimentation within this aspect of the subsystem. An important aspect for consideration is that a spherical buoy is the best shape to capture energy from a wave. To optimise the buoy, the motion of your particular buoy should be investigated with real waves to see how it works. Ideally, the buoy moves in unison and follows the surface of the wave well so that energy is not lost with the buoy bouncing erratically or, if it consists of separate parts, moving out of unison with each part counteracting the motion of the other. If separate parts are used as described in the

Figure 2 - Bicycle Point Absorber Subsystem 1: Linear to Rotational Motion
prototype, it may be beneficial to build a system whereupon the parts are rigid with respect to one another. For example, a flat, solid grid may be constructed using wood which holds all the bottles together so that they move in unison following the wave surface.

![Figure 3- Buoy made from Milk Bottles](image)

The buoy is tied to a rope, which is in turn reeled from a spool. Hence, as the buoys falls into a wave trough, the force of the rope causes the spool to unwind. Through the use of a counterweight (Figure 4) and a locked, reverse-direction spool, the rope is re-wound whenever the buoy is lifted by a wave. Therefore, the rope retains tension and moves back and forth with the waves. In the case of the prototype, plastic fishing reels were used as spools and a 3L milk bottle was filled with 1L of water and used as the counterweight. The ropes come from the spools towards the edge of the jetty, are threaded through galvanised pulleys (as available commercially), with one rope connected to the buoy and the second rope connected to the counterweight. At least 1m of spare rope should be present on the other side of the pulley connected to the counterweight, this allows for unimpeded function for wave and tidal movements. The pulleys provided a smooth transition from the buoy and counterweight to the rotation of the spools.
From here, the bidirectional motion of the spools winding back and forth with the motion of the waves must be made unidirectional to effectively spin a rotational generator. Therefore, the team bolted the spools into the crankset of a bicycle, as shown in Figure 5. The linear motion of the buoy is then transferred through the rope and pulley system, rotating the spools and hence working the bicycle drivetrain, providing energy in the bicycle as rotational kinetic energy. A breakdown of the components in Subsystem 1, alternative materials, and where they can be acquired is included in Table 2-7.
The first listed materials were used for the prototype. Other listed materials are proposed alternatives.

**Table 2- Buoy Components**

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk cartons (12 3L cartons or 18 2L cartons)</td>
<td>Trash and recycling</td>
<td>Easy to source. Has handles, making it easier to bind together.</td>
</tr>
<tr>
<td>Empty container or vessel (oil drum)</td>
<td>As above</td>
<td>Easy to source.</td>
</tr>
<tr>
<td>Bottles (drink bottles)</td>
<td>As above</td>
<td>As above</td>
</tr>
<tr>
<td>Buoyant objects (wood, coconuts)</td>
<td>As above</td>
<td>As above</td>
</tr>
</tbody>
</table>

Considerations:
Bottles or cartons with a handle are easier to attach to a rope.
The buoy must be heavy enough to supply a large torque when it falls such that the drivetrain is stimulated, however it should not be too heavy or its inertia may limit the range of motion. Experience suggests that a weight of around 18L of water over 13 bottles works well, but it is suggested that other weights are trialed. By filling containers with different amounts of water, the weight can easily be adjusted.
It is beneficial for wave energy capture to have the buoy as spherical as possible. It is also better to have the buoy move in unison as much as possible if it consists of separate parts.
A grid can be constructed for such a purpose to stop parts bouncing independently from one another.

**Table 3- Power Transfer Cable Components**

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
</table>
| Rope        | Sea-faring equipment | Provides durability in ocean conditions. Salt water limits the lifespan of many materials and this aspect requires a material that can
also withstand a reasonable level of tension for a given weight.

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical cord</td>
<td>Electrical appliances in trash. Can be salvaged from old appliances such as vacuum cleaners, audio-visual equipment</td>
<td>Easy to source, provides good friction on spool, wire may corrode but the cord is insulated with rubber which will last for this application.</td>
</tr>
</tbody>
</table>

Considerations:
The power transfer cable must bend around the radius of the pulley and the radius of the spool easily.
Using a thinner cable allows a greater length to be stored on the spool which means that the buoy can be further out to sea if necessary.
Elasticity in the transfer cable will mean losses as the energy is used in stretching the cable as opposed to transferring it to the drivetrain.
As the cable will be in strong tension it must be very durable so that it does not need to be replaced on a regular basis.

Table 4- Pulley

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanised Pulley</td>
<td>Sea-faring equipment, trash and recycling</td>
<td>A range of pulley options could be found as scrap or purchased for very little. Less prone to corrosion.</td>
</tr>
<tr>
<td>Bicycle rim style wheel (without tyre)</td>
<td>Any bicycle</td>
<td>Will be found with the bicycle needed for the system.</td>
</tr>
</tbody>
</table>

Considerations:
A bicycle is a key component of the drivetrain, however its front wheel is not used in this application and can therefore be used as a pulley.
The pulley acts as a guide for the spool to ensure that it remains in an adequate position on the spool.
It is also used to redirect the cable from the jetty down to the water and may not be required if an alternate solution is found.
Table 5 - Spool Components

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fishing spool</td>
<td>Fishing equipment</td>
<td>Easier to find this equipment along the coast, made of a non-corrodible, break resistant material</td>
</tr>
<tr>
<td>Electrical cord spool</td>
<td>Appliances with retractable electrical cords, such as vacuum cleaners.</td>
<td>As above, although may be more prone to breaking.</td>
</tr>
</tbody>
</table>

Table 6 – Drivetrain Components

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-wheel Bicycle</td>
<td>Scrap or recycle</td>
<td>Provides smooth bearings and a gearing system to optimise the system.</td>
</tr>
</tbody>
</table>

Considerations:

A bicycle is most appropriate because the rear hub contains a freewheel (if not fixed gear) unidirectional bearing system. A fixed gear bicycle will not work as the rear wheel will spin back and forth causing an abrupt stop-start motion which would not translate well to the operation of a rotational generator.

A bicycle with a number of gears will allow the system to be easily adjusted for different wave conditions by the user.

The chain wheels, chain and back wheel are the components of the bicycle that are critical for the system. Components such as the front wheel, forks, handle bars and seat are either not used at all, or only used for structural support. Their condition is not a priority.

Functioning derailleurs are advantageous but not necessary. Gear changes will be infrequent if present at all, and can be changed manually by the user without a derailleur.
### Table 7- Flywheel Components

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel banding (30 m, 5kg)</td>
<td>Trash and recycling</td>
<td>Correct sized banding will fit well inside the tyre. It is also easy to find scrap metal to use.</td>
</tr>
<tr>
<td>Concrete</td>
<td>Purchased from construction sites</td>
<td>After initial installation, the concrete will remain as a long term solution.</td>
</tr>
<tr>
<td>Rope or cable</td>
<td>Trash and recycling</td>
<td>Easy to fix to the inside of the tyre and find as scrap material.</td>
</tr>
</tbody>
</table>

**Considerations**

The role of the flywheel is to increase the inertia in the drivetrain, momentum when spinning and reduce the impulsive torques on the generator. In some systems, it may not be necessary.

The extra weight should be placed inside the back tyre, and distributed as evenly as possible. Uneven distribution will result in vibrations and inefficiency.

If the flywheel is too heavy, the torque produced by the buoy on the drivetrain may be insufficient to spin the system adequately. However if the flywheel is too light, it will not work as desired. Experimentation may be necessary and with the prototype, 5kg was an effective weight.
Subsystem 2 – Generator and Frame

Subsystem 2 converts the rotational kinetic energy of the drivetrain (the bicycle chain wheels and back wheel) into electrical energy through the use of a generator (Figure 7). There are a large range of different generators that can be used, and these dictate the electrical system required in Subsystem 3. The generator needs to be mounted against the bicycle wheel such that friction is sufficient to spin the rotor reliably, but not too strongly as to slow the flywheel unnecessarily. In this case, we assume the use of a rotational generator. A wooden frame to hold the generator up against the rotating back wheel and aid in stabilising the entire system was constructed. A spring between a support for the bicycle and a support for the generator provided optimal frictional contact, this was easily adjustable by using rope to reduce the spring stretch. Instructions for converting a ceiling fan into a generator are provided in Section 2, other solutions are also provided in Table 8 below.

Figure 6 - Bicycle Point Absorber Subsystem 2: Generator and Frame
The basic premise of a generator is the use of moving magnets to create a changing magnetic field. This “pushes” electrons in the copper coils, inducing a current. The easiest method is to find a generator with permanent magnets already in the system. Direct current or DC motors are the simplest solution as they contain permanent magnets within and create DC suitable for storage in a battery. This eliminates the need for rectification (where alternating current is converted to direct current) and the sourcing of permanent magnets. While this may seem simple, the drawback is that typical DC motors are very small and are generally inefficient as generators. Small DC motors can be found in printers and other electronic appliances where there is rotational movement. A larger DC motor is a more ideal solution and can be found in larger appliances such as treadmills.

If an appropriate DC motor cannot be sourced, another option is retrofitting an AC motor. AC motors do not contain permanent magnets, and so in order to use them as effective generators modification is necessary. Alternatively, they can still be used if reactive power is supplied to magnetise the motor in the case of induction machines. AC motors are more suitable for some direct applications such as powering a lightbulb, but for storage applications they require a more complicated electrical system (Subsystem 3). The motor is split into two components: the stator (stationary) and the rotor (rotating) (Figure 8). The rotor is often inside the stator, but not always. The stator contains copper coils. If you add permanent magnets to the rotor and then spin it, a varying magnetic field encompasses the copper coils causing electrons to experience a force and hence producing electricity.
The frame can be constructed in many different ways depending on the specific needs for the system. A simple wooden frame that holds up and stabilises the bicycle can be used so that the system can be left unattended during operation. Mounting the generator on bolts between two planks allows for easy removal of the generator and tensioning. The planks should be free to pivot, and a spring installed so that the correct pressure can be maintained between the drivetrain and the generator. If the pressure is too low, the generator will slip on the wheel, but if the pressure is too high, then the pressure will cause extra losses in the system. In order to maintain an optimum pressure, a spring should keep tension between the pivoting planks and the bicycle wheel, as shown in Figure 9.
Details of potential components for Subsystem 2 are included in Table 8 and Table 9.

**Table 8 - Generator Components**

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC motors</td>
<td>Some household appliances, office equipment (e.g. printers, treadmills)</td>
<td>DC output is suitable for charging a battery.</td>
</tr>
<tr>
<td>AC motors</td>
<td>Some household appliances, office equipment (e.g. ceiling fans, some washing machines)</td>
<td>Longer lasting option than DC motor, has potential to produce more power.</td>
</tr>
<tr>
<td>Car/motorbike alternator</td>
<td>Car/motorbike</td>
<td>Designed specifically to charge a car battery when rotated quickly enough.</td>
</tr>
</tbody>
</table>

Considerations:
For a ceiling fan conversion, magnet placement should be as close as possible to the copper coils to increase magnetic field strength.
DC motors will wear out reasonably quickly. Therefore larger ones should be used if possible and spare motors will need to be on hand.
A car alternator requires reactive power to excite the machine before extractable power is possible. Torque issues may also exist and therefore subsystem 1 & 2 will need to be modified.

**Table 9 - Frame Components**

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooden planks with nuts, bolts and screws</td>
<td>Trash or recycling, purchased</td>
<td>Easy to source.</td>
</tr>
</tbody>
</table>

Considerations:
Frame can be constructed from many different materials and in many different designs.
A tensioning spring is very beneficial and should be include in all designs where possible.
As the frame will be exposed to a corrosive environment, suitable material selection and protective measures should be in place.
Subsystem 3 – Charge Controller

Figure 10 - Bicycle Point Absorber Subsystem 3: Charge Controller

The charge controller converts the power output of the generator into a useful input level for a battery. If an AC generator is used rectification to DC will be required to charge a battery. Depending on the voltage output of the DC or AC generator, a transformer may need to be used to bring the level to an acceptable voltage. In the case of the 2015 Honours Team where a 0-30V open circuit voltage solar charge controller was used, the ceiling fan generator produced a voltage too high for 12V battery charging and a 120-20V transformer was used for each coil. The correct voltage range for the charge controller is crucial for safe operating. The particular generator that is built by you must be tested for open circuit voltage and short circuit current which defines the upper limits of the generator. To do this, connect
a multimeter across the generator output terminals and work the generator to record maximum expected rotational speeds. With this, you can look at the operating requirements of your charge controller and adjust the outputs with transformers as required. Alternatively, some charge controllers simply dump the power to a dummy load when it falls outside of battery charging ranges. In this case, the biggest consideration is safety discussed further in this section. A capacitor connected in parallel with the charge controller can be salvaged to aid in smoothing the erratic, peaking power output due to inconsistent waves. A capacitor is like a smaller intermediary battery that will be charged by the generator when the waves have spun the system, then discharge into the battery when the generator is not being worked by a wave. This is helpful in maintaining power levels within the correct charging range. Purchasing a solar charge controller is an efficient option, while plans for construction of a charge controller are also supplied in Table 13.

*Table 10 - Transformer*

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>120-20V</td>
<td>Cathode ray tube television</td>
<td>Found in trash or recycling. May or may not be necessary.</td>
</tr>
</tbody>
</table>

Considerations:
Any available transformer can be used if the produced voltage is too high or too low. If the only available transformer steps the voltage down too much, then more generators will need to be used. This is dependent on the generator output.
Test the generator output with a multimeter to see if a transformer is required, work the system over a range of speeds including the expected maximum for a safety margin.
As transformers are designed for certain voltages and frequencies, the erratic nature of the system operation will results in the transformer not stepping down at the exact ratio due to frequency differences in the power.
Table 11 - Rectifier

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full wave bridge rectifier</td>
<td>AC to DC adaptors such as a laptop charging cable General power electronic devices (e.g. monitors)</td>
<td>Found in trash or recycling, utilizes maximum available power.</td>
</tr>
<tr>
<td>4 simple diodes</td>
<td>As above</td>
<td>Easy to source.</td>
</tr>
</tbody>
</table>

Considerations:
If 1 diode is used, this would be a half wave rectifier and half of the AC waveform will be lost, if 4 diodes can be installed in a Wheatstone bridge formation then the maximum available power will be utilized.

Table 12 - Capacitor

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>270-10000μF</td>
<td>General power electronic devices (e.g. stereos)</td>
<td>Aids in smoothing power output of generator.</td>
</tr>
</tbody>
</table>

Considerations:
Capacitors can range from 10μF to above 10000μF, the capacitor values given above are an appropriate size to smooth power output levels.

Table 13 - Charge Controller

<table>
<thead>
<tr>
<th>What to use</th>
<th>Where to find it</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar charge controller, 0-30V open circuit system</td>
<td>Purchased from store</td>
<td>An efficient option.</td>
</tr>
<tr>
<td>Self-made charge controller</td>
<td>Components can be purchased or salvaged from electrical devices (radios, computers, etc.)</td>
<td>Cheaper option. A good example one which can be built with easily sourced materials from Davis (2014)(^1)</td>
</tr>
</tbody>
</table>

\(^1\) [http://www.mdpub.com/555Controller/](http://www.mdpub.com/555Controller/)
Safety Considerations:

Electricity:
Due to the potential for a high voltage output from the generator, all electrical devices must be insulated properly. Electrical components should not be touched by hand when the system is operating. When working on the electrical system the generator must be disconnected from the back wheel so that no power is generated. As a capacitor is used in parallel with the battery, the capacitor must be discharged with resistors when charging has concluded. Do this by short circuiting the capacitor to a resistor. To ensure that the charge controller remains functional and does not pose any safety issues, it is very important to keep the charging voltage in the correct safe operating range. Appropriate wire sizes must be used to prevent a fire hazard if the current generated exceeds the current carrying capability of the cables used.

Moving and Sharp Parts:
The waves will cause movement in the ropes, spools, bicycle pedals, chain and back wheel. Therefore appropriate space must be kept between personnel and moving parts. Gloves must be worn when dealing with moving parts. To stop the back wheel quickly, the brakes on the bike handle can be used. To stop generator movement quickly, the brakes can be used and the tensioning spring can be removed so that no contact exists between the wheel and generator. The bike should also be firmly attached to the wooden frame, which in turn will need to be attached to the jetty. This will ensure that larger waves do not pull the system over or into the ocean.

Water:
As electricity is being produced, it is very important that water does not come in contact with any of the electrical systems. As the system only has the buoy in the water and the rest of the WEC system is on a jetty, issues of water to electrical component contact due to waves are minimised. A shield such as a weighed down tarpaulin over the entire system to stop rain is suggested. This shield will also aid in slowing down corrosion.

Battery:
If the charge controller becomes faulty and incorrect charging values are put into the battery there is a chance that the battery can leak or explode. The battery should be placed into its own ventilated separate container so that leaks are isolated and hazardous gases can escape.
Final Statement:

These guidelines are only one solution to building a wave energy converter to charge a battery. Alterations and adaptations of the wave energy converter can be made for your personal wave conditions, geography and easily sourced materials. The components listed do not have to be sourced as some of them can also be made either by you or with a combination of different materials. Use your imagination and good luck!
Section 2: Step by step construction

Spool Construction Guidelines:

**Materials:**
2x Hand fishing spools, hard plastic material is preferable, same sizes are preferable
3-5x Nuts and Bolts (long enough to pass through the width of both spools and the crankset on the bicycle)
1x Rectangular wooden block that fits into the side of the fishing reel
1x Drill and drill set
6-8x zip ties
Thin rope to be spooled over reels
Duct tape
Optional: Glue or silicon

**Construction:**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zip tie the two fishing reels together through pre-constructed holes or through self-drilled holes.</td>
<td>![Image of zip tied spools]</td>
</tr>
<tr>
<td>Cut away the spare zip tie material and tape over the protruding material. This is to make sure that the rope does not catch on the zip ties.</td>
<td>![Image of spools with zip ties removed and tape applied]</td>
</tr>
<tr>
<td>Drill 1 hole into each spool wall, just wide enough for the rope to pass through.</td>
<td>![Image of spool with hole drilled]</td>
</tr>
<tr>
<td>Thread half of the rope onto one spool, tying a knot into the rope on the inside of the spool.</td>
<td>![Image of spool with rope threaded through]</td>
</tr>
</tbody>
</table>
Thread the remaining half of the rope onto the other spool, tying another knot next to the drilled hole to remove rope movement.

Loop the rope on the inner spool in a counter clockwise direction and the rope on the outer spool in a clockwise direction.

Cut away the pedal on one side then drill 3-5 holes into the spokes of the crankset. Making sure that the bolts can just fit through the holes.

Drill 3-5 corresponding holes into the wooden block that line up with the spoke holes.

Place all 3-5 bolts through the spoke holes, place the bolts through the spools and into the holes of the wooden block. Place the nuts onto each bolt, tightening as required. If the fishing reels can have holes drilled into them that line up with the bolts without compromising the integrity of the structure, this will be beneficial to reduce lateral movement.
<table>
<thead>
<tr>
<th>Place glue/silicon (Loctite, nail polish) over the nuts and bolts to stop movement and aid in corrosion prevention.</th>
</tr>
</thead>
<tbody>
<tr>
<td>The inner spool rope will be connected to the buoy and the outer spool rope will be connected to the counterweight.</td>
</tr>
</tbody>
</table>
Generator Construction Guidelines:

**Materials:**
1+ ceiling fan
32 magnets sized to minimise the distance between the banding and the rotor (1-4 magnets per coil inside the fan, in this case 2x was used)
3m of metal banding (approx. 120mm height and 3mm thick)
Multimeter
Duct tape
Toolkit

**Construction:**

Identify the ceiling fan with the highest rated amperage from the production sticker. This fan will be the generator (NOTE: 2 fans are shown in this process, one that is not used due to a lower rating and less preferable housing structure, see step 9)

Remove all blades from the fan using a screw driver.
Remove the top plug as shown.

Proceed to removing the cable cover.

Cut the light cables at the bottom and remove the light assembly by removing the bolt.

Identify the 2 coils coming from the fan (two cables per coil), cut these together and keep them protected afterwards. Remove the remaining cables and the protective frame.

Identify the pairs of coils, to do so, attach a multimeter set to measure resistance to one wire and touch the other three wires. A reasonable value indicates a connection and completion of the loop. Tape the two ends of the coil together to make it easy to
recognize them later. If the resistance is infinite, the circuit is not completed and the two wires are not connected (not a coil).

Remove the screws keeping the fan housing in place.

Take the housing off to identify the inner coils and the iron core.

Remove the iron core as the metal banding will be placed in the same spot. (NOTE: this golden fan has inconvenient screw positions which will interfere with the metal banding, this can be dealt with or a different fan can be used.)

Place metal banding on the frame of the fan.

Tape and glue the banding tightly in place. The distance between the banding and the inner core should be as small as possible.
Insert 2 pairs of magnets equally across the banding to correspond with each copper coil. (NOTE: the two magnets that are side by side must have the same pole facing inwards. The pole direction from one pair to the neighboring pair must be opposite, therefore it will be NSNSNSNS… around the entire generator.)

Place the housing cover back on the fan to protect it from outside conditions.
Buoy and Counter Weight Guidelines:

Materials:
- 12+ 3L milk bottles with handles
- Rope
- 3L milk bottle for counter weight
- 2x galvanised pulleys

Construction:
- Fill all milk bottles approximately 2/3 full of water. This will ensure that the bottles are heavy enough to work the system and buoyant enough to float atop the waves.
- Tether all milk bottles together as tightly as possible by threading the rope through the handles and tying it off. It is worth tying off two separate loops that keep the buoy tied together in case one loop gets damaged.
- Thicker rope can be used for this section and then tied to the thinner spool rope, this will reduce rope extension and therefore movement losses.
- Recommended: a secondary rope can be tied from the jetty directly to the buoy with extra slack, this is a backup option in case the original rope tears for any reason.

Counter weight construction:
- Fill the 3L milk bottle with approximately 1L of water. As the counterweight brings the bike back to equilibrium and little resistance exists in the bicycle for reverse pedalling, it does not need to be very heavy.

Considerations:
- Tie 2 pulleys onto the side of the jetty, allowing the spool ropes to pass through. These pulleys will reduce frictional losses. Connect the outer spool rope to the counter weight bottle, making sure that there is approximately 1.5 meters of rope on the outer side of the pulley. This is to ensure the counter weight does not hit the pulley and stop the system due to tidal or wave movement. Tie the inner spool rope onto the thicker buoy rope, making sure there is also 1.5+ meters on the outer side of the pulley. The rope connecting to the buoy will be wound on clockwise onto the spool, therefore as the buoy falls with the waves it will work the system. The rope connecting to the counterweight will be wound counter clockwise onto the outer spool, therefore as the buoy is lifted by the waves, this weight will take the slack of the system. The buoy rope should be installed on the inner spool as this will create less sideways force on the bicycle.
Back Wheel Flywheel Construction:

Materials:

Back wheel of bicycle (including tyre)
Metal banding to add to the inside of the tyre
Tools to remove and replace tyre onto wheel
Optional: inner tube + space tube, glue or silicon

Construction:

Remove the tyre from the wheel.

Place the metal banding into the tyre.

Replace the tyre onto the wheel.

If the banding is moving too much, glue it to the inside of the tyre to stop banding movement. Optionally place a spare uninflated tube on the inside of the banding and then place another tube inside of that. Place the tyre onto the wheel and inflate the inner most tube, this will push the banding to the walls of the tyre.
Wooden Frame Construction:

Materials:

- Saw to cut wood
- Drill and drill set
- 3m of wooden planks (approximately 20mm thick will suffice)
- 12x 45mm screws
- 2x nuts and bolts (60mm)
- Hook nails
- Bolt to hold the generator to the frame

Construction:
As a large variety of frames can be constructed, images and tips for construction are included instead of a step by step approach.

Two planks (A) are recommended to hold up the bike. Small holes can be drilled near the top with a zip tie or rope threaded through to stabilise the bike to the frame.

Planks B were attached to the bottom frame with the nuts and bolts so that they can be moved back and forth. A hole is drilled towards the top end of B, with the large bolt through one plank and another hole to hold the fan in the other plank.

Hook nails are installed at the top end of both A and B. A rope and spring are used between the hook nails to keep tension between A and B.

The frame will need to be attached firmly to the bike and then installed onto the jetty. This will allow the system to be left unattended during high swell days. The frame can be extended to also hold the bicycle handles for extra stability.
Charge Controller System:

Materials:
- 1x multimeter
- 1x wire cutting and crimping tool
- Assorted wires for connections (2m should suffice)
- 2x 120V-20V transformers
- 2x Full wave bridge rectifier
- 1x 420-10000μF capacitor
- 1x Solar charge controller

Construction:
Connect each pair of coils from the generator to the transformer inputs. 
Connect the output of both transformers to the full wave bridge rectifiers. 
Connect the output of the rectifiers in series. 
Connect the output of the rectifiers to the capacitor and charge controller input in parallel. 
Connect the charge controller output to the 12V battery.

Figure 12 - Subsystem 3 Schematic